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A CRITICAL SURVEY AND ANALYSIS OF AIRCRAFT SPLINE FAILURES.(U)
AUG 71 M L VALTIERRA, R D BROWN, P M KU   N00156-70-C-2156
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Report No. RS-574

A CRITICAL SURVEY AND ANALYSIS OF AIRCRAFT SPLINE FAILURES

In Support of

NAVAL ANALYTICAL REWORK PROGRAM

FINAL REPORT
Contract N00156-70-C-2156

M. L. Valtierra
R. D. Brown
P. M. Ku

to

Naval Air Engineering Center
Department of the Navy
Philadelphia, Pennsylvania 19112

August 18, 1971

SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO HOUSTON

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SWRI-2156	2. GOVT ACCESSION NO. (9)	3. RECIPIENT'S CATALOG NUMBER Final rept.
4. TITLE (and Subtitle) (6) A Critical Survey and Analysis of Aircraft Spline Failures.		5. TYPE OF REPORT & PERIOD COVERED Research Report, ~~January 1970-August 1971~~, 6. PERFORMING ORG. REPORT NUMBER 24 Jun 70-18 Aug 71
7. AUTHOR(s) (10) M. L. Valtierra, R. D. Brown P. M. Ku		8. CONTRACT OR GRANT NUMBER(s) (15) N00156-70-C-2156
9. PERFORMING ORGANIZATION NAME AND ADDRESS Southwest Research Institute San Antonio, TX 78228 410 173		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (11) 62760N/53-532/403
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Weapons Engineering Support Activity (ESA-116) Wash. Navy Yard, Washington, DC 20374		12. REPORT DATE 18 August 1971 13. NUMBER OF PAGES 225
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Same as 11. (12) 246p.		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited. (14) SwRI-RS-574, SwRI-2156		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) Approved for public release, distribution unlimited.		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Aircraft Spline Failures Aircraft Accessories Mechanical Power Transmission Spline Lubrication		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The objectives of this program were: (1) to perform a survey and analysis of the current technology in the design and maintenance of aircraft splines, (2) to emphasize reduced maintenance, extended life, and improved reliability, (3) to identify improvement programs for early reduction of maintenance problems, and (4) to forecast technology gaps for long-range reduction of maintenance problems. → next page		

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S/N 0102-LF-014-6601

410 173

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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A total of 91 spline problem areas were identified by the following: NAVAIREWORKFAC(s): 55; Air Force: 20; ARADMAC: 12; commercial airlines: 1; and equipment manufacturers: 3. The spline problem areas identified by the NAVAIREWORKFAC personnel are associated with 40 and 70 percent of the Navy's fixed and rotary wing aricraft types, respectively. They represent 45 percent of the Navy's aircraft types, based on the 3M aircraft listing.

Report No. RS-574

SOUTHWEST RESEARCH INSTITUTE
8500 Culebra Road, San Antonio, Texas 78228

Department of Fluids and Lubrication Technology

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APPROVED:

P. M. Ku

P. M. Ku, Director
Department of Fluids and
Lubrication Technology

FOREWORD

This report was prepared at Southwest Research Institute under Contract N00156-70-C-2156, and covers work performed during the period of June 24, 1970 to August 18, 1971. The work was conducted in support of the Analytical Rework Program of the Naval Air Systems Command, Washington D. C., under AIRTASK WR-1-5060, Application of New and Improved Materials and Processes in support of the Analytical Rework Program. Technical guidance was provided by the Naval Air Development Center, Warminster, Pennsylvania.

The authors deeply appreciate the assistance rendered in various ways throughout the program by Mr. A. J. Koury of the Naval Air Systems Command; Messrs. M. J. Devine, L. Stallings, and E. Jewell of the Aeronautical Materials Laboratory, Naval Air Development Center; Mr. E. J. Deemer, Naval Air Systems Command Representative Atlantic, and Mr. G. E. DeLong, Naval Air Systems Command Representative Pacific. Acknowledgment is further extended to the following Naval Air Rework Facilities personnel for their assistance and cooperation: Messrs. L. S. Bercegeay (Cherry Point), J. Cahill (Norfolk), E. L. Donaldson (Jacksonville), H. Katz (Quonset Point), R. J. Palk (North Island), A. W. Tucker (Alameda), and H. Yesnes (Pensacola), as well as their colleagues too numerous to mention individually.

Appreciation is due Lt. Cdr. J. F. Jaggard, Naval Air Station, Corpus Christi, Texas; Lt. Cdr. Burchfield, Naval Air Station, Kingsville, Texas; and Messrs. S. H. Boberg and J. D. Wilson and Colonel L. Jones, Jr., of ARADMAC, Naval Air Station, Corpus Christi, Texas.

Assistance was provided by Messrs. J. W. Hollaway, S. Madrid, Jr., H. Godwin, and D. G. Harris of the Service Engineering Division, Kelly Air Force Base, Texas; and Messrs. E. M. Haberlandt, L. Ferringer, K. Knight, and Major W. J. Bland of the Service Engineering Division, Tinker Air Force Base, Oklahoma.

Appreciation is also due the following companies for their contributions to this project: American Airlines, United Airlines; AiResearch Manufacturing Company of Arizona, The Bendix Corporation, The Boeing Company, Lockheed Aircraft Corporation, Sundstrand Corporation; Chevron Oil Company, Shell Oil Company, and Texaco Incorporated.

ABSTRACT

The objectives of this program were: (1) to perform a survey and analysis of the current technology in the design and maintenance of aircraft splines, (2) to emphasize reduced maintenance, extended life, and improved reliability, (3) to identify improvement programs for early reduction of maintenance problems, and (4) to forecast technology gaps for long-range reduction of maintenance problems.

Survey forms were developed to identify specific spline problem areas. Visits were made to seven Naval Air Rework Facilities, two Naval Air Stations, two Air Force Bases, ARADMAC, two commercial airlines, five equipment manufacturers, and three lubricant manufacturers in an effort to collect all relevant available information. Based upon the information thus obtained, supplemented by the findings from considerable research and development work conducted at SwRI over the past eight years, an overall analysis of the problem of aircraft spline failures and their possible means of mitigation was then made.

A total of 91 spline problem areas were identified by the following: NAVAIREWORKFAC(s): 55; Air Force: 20; ARADMAC: 12; commercial airlines: 1; and equipment manufacturers: 3. The spline problem areas identified by the NAVAIREWORKFAC personnel are associated with 40 and 70 percent of the Navy's fixed and rotary wing aircraft types, respectively. They represent 45 percent of the Navy's aircraft types, based on the 3M aircraft listing.

With respect to the problem areas, the main conclusions are as follows:

1. Splines located inside the engine or gearbox generally exhibit minimal wear. These splines usually operate at medium to heavy loads. Furthermore, they are enclosed within the engine or gearbox envelope and generally receive intermittent or continuous oil lubrication.

2. Splines located in the airframe generally exhibit minimal to moderate wear. These splines are used in applications such as flap and slat actuators, elevator trim actuators, landing gears, and others. For the most part, these splines are grease-lubricated, and they experience intermittent operation at light to medium loads.

3. Interface splines which connect two components have provided the majority of the wear problems on both fixed and rotary wing aircraft. These splines are usually grease-lubricated, and experience

continuous operation at moderate to heavy loads at high rotational speeds.

In order to reduce maintenance, extend life, and improve reliability of the interface splines, which represent by far the most critical problem area, it is recommended that the following immediate improvement programs in the rework area be considered by the Naval Air Systems Command: (1) misalignment control, (2) improved liaison between organizations, (3) lubrication of helicopter main rotor mast, (4) grease selection, (5) more frequent relubrication, (6) more thorough cleaning, (7) reverse splines in gearbox, and (8) utilization of the spline muff.

In the domain of technology gaps for long-range improvement, it is recommended that the Naval Air Systems Command consider the following: In the rework area: (1) improved misalignment measurement, (2) improved misalignment control, (3) improved wear measurement, and (4) improved rejection criteria. In the research and development area: (1) improved design standards, (2) improved spline materials, (3) investigation of plastic and metallic surface coatings, (4) investigation of expendable bolt-on splines, (5) investigation of expendable spline muffs, and (6) improved lubricants.

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GLOSSARY OF TERMS
(Standard Naval Terminology Unless Otherwise Indicated)

AMD	Aircraft Maintenance Department
AND	Air Force-Navy Aeronautical Design Standard
AOH	Analytical Overhaul
ANSI	American National Standards Institute
ARADMAC**	U.S. Army Aeronautical Depot Maintenance Center
ARC	Accessory Record Card
AS	Aerospace Standard
ASO	Aviation Supply Officer
AVSCOM**	U.S. Army Aviation Systems Command
AYC	Aircraft Accessory Change
CER	Complete Engine Repair
CERFAC**	Complete Engine Repair Facility
CI	Calendar Inspection
CIP*	Component Improvement Program
COMNAVAIRLANT	Commander, Naval Air Force, U.S. Atlantic Fleet
COMNAVAIRPAC	Commander, Naval Air Force, U.S. Pacific Fleet
CR	Commercial Rework
DIR	Disassembly and Inspection Report
EBN	Engine Bulletin Number
EC	Engineering Cognizance
ECP**	Engineering Change Proposal
E&E	Examination and Evaluation
EIR**	Equipment Improvement Report
EPN	Engineering Program Notice
EUR	Electonic Unsatisfactory Report
FSN	Federal Stock Number
IRAN*	Inspect and Repair as Necessary
IRON**	Inspect and Repair Only as Needed
ISO	International Standards Organization
LES	Local Engineering Specification
3M Reports	Maintenance, Material, Management Reports
MOT	Maximum Operating Time
MRC	Maintenance Requirement Cards
MRL	Master Repair List
MS	Military Standard
MTBF*	Mean Time Between Failures
MUSF	Master Usage File
NADC	Naval Air Development Center
NAEC	Naval Air Engineering Center
NAS	Naval Air Station
NASC	Naval Air Systems Command

NATC	Naval Air Test Center
NATSF	Naval Air Technical Service Facility
NAVAIR	Naval Air Force Specification
NAVAIREWORKFAC	Naval Air Rework Facility
OH	Overhaul
PAR	Progressive Aircraft Rework
PPB	Power Plant Bulletin
PPC	Power Plant Change
PSP*	Product Support Program
QAD	Quality Assurance Department
QEC	Quick Engine Change
RFI	Ready for Issue
SAE	Society of Automotive Engineers
SEO**	Service Engineering Order
SQ	Squadron
SR	Structural Repair
TBO	Time Between Overhaul
TM**	Technical Manual
T. O. *	Technical Order
TMOT	Target Maximum Operating Time
UR	Unsatisfactory Report
WO	Work Order
WR**	Work Requirement

*Air Force Terminology
**Army Terminology

I. INTRODUCTION

A. Program Objectives

The objectives of this program were: (1) to conduct a survey and analysis of the current technology in the design and maintenance of aircraft splines, (2) to emphasize reduced maintenance, extended life, and improved reliability, (3) to identify improvement programs for early reduction of maintenance problems, and (4) to forecast technology gaps for long-range reduction of maintenance problems.

B. General Approach

The general approach used in this survey consisted of collecting information relative to spline failure problems from sources including seven Naval Air Rework Facilities, two Naval Air Stations, two Air Force Bases, ARADMAC, two commercial airlines, five equipment manufacturers, and three lubricant manufacturers. Much of the information was collected during a visit to each of the organizations; but additional information was also collected by other means of communications and from other sources recommended by the personnel visited. Most of the information was elicited by means of survey questionnaires designed by SwRI, with additional information being obtained from appropriate specifications, reports, etc., drawing heavily upon the research and development work performed by SwRI in the past eight years, all under Navy contracts or subcontracts. An analysis was made, which led to a critical appraisal of the state-of-the-art. Finally, recommendations were presented relating to immediate improvement programs in the rework area, as well as long-range technology gaps in the rework area and in the research and development area.

Specific requirements of the contract work statement are given below:

1. Results of all trips made and discussions held.

2. A bibliography with abstracts of significant technical reports, development projects, and component improvement programs which are specifically cited by the personnel visited.

3. A compilation and comparison of design, materials, etc., regarding operating field results at NAVAIREWORKFAC(s). Spline configuration, operating environment, and lubrication will be included.

4. A summary review of significant field failure reports made available by the Navy and commercial vendors and manufacturers with special emphasis to relate such failures to present design techniques or technology gaps.

5. A critical review of all information collected concluding with a statement of the state-of-the-art.

6. Recommendations that will guide AMD (p) and Naval Air Systems Command Headquarters in identifying component improvement programs which will lead to early reduction of specific maintenance problems, extend spline wear life, and also forecasting needed research programs which will provide future long-range reductions in maintenance requirements.

C. Aircraft Splines

A large number and variety of splines are used in a modern aircraft. For example, in the single-engine A-4 aircraft shown in Figure 1, there are 174 spline connections, excluding those located inside accessories such as accessory gearboxes, fuel pumps, cameras, and instruments. This count was obtained by examination of the Illustrated Parts Breakdowns of the NAVAIR 91-40AVC-4-2, -3, -4, -5, -6, -7, -8, and -9. The number of spline connections used in eight general categories of applications are as follows:

Engine:	36
Air Frame:	16
Landing and Arresting Gear:	37
Flight Control:	34
Ejection and Cockpit Equipment:	28
Power Control:	10
Guns:	10
Emergency Electrical Power:	3
Total	174

These splines are normally associated with three areas during a PAR, as illustrated in Table 1. The three areas are: aircraft accessories, engine accessories, and engines and engine components, each having various inspection periods.

In a multi-engine aircraft, the number of spline connections can easily exceed 200 or more.

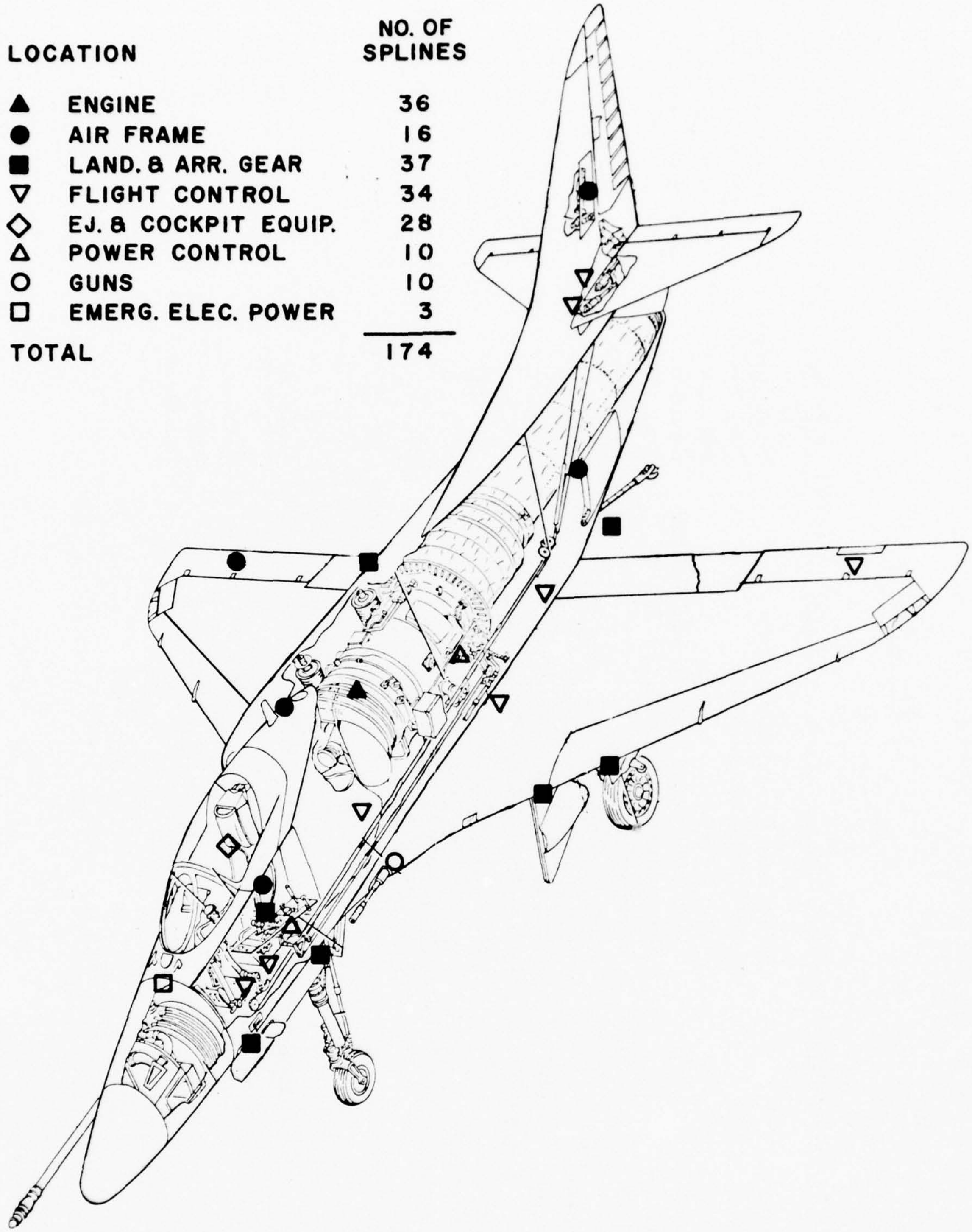

FIGURE 1. LOCATION OF SPLINE CONNECTIONS ON THE A-4 AIRCRAFT

TABLE 1. LOCATION OF AIRCRAFT SPLINES

Aircraft PAR

Aircraft Accessories		Engine Accessories	Engines and Engine Components
Hydraulic pump	Fuel transfer pump electric	Fuel pump	All internal components
Generators	* Speed brake transmitter	Fuel control	of engines, such as:
CSD, CSDS	* Aileron motor	Oil pump	Scavenge oil pumps,
Starter generator	Fuel boost pump (submergible elec)	Gearbox	Engine governors, etc.
Starter electric	* Horizontal stabilizer position Transmitter	Shaft power	
Starter turbine		Magnetos	
* Tachometer	* Flutter dampener (rudder)		
* Ram air turbines	* Flutter dampener (Aileron)		
* Air conditioning ram air	* Wing tip fuel dump valves		
* Fuel flow transmitter	* Wing tip fuel transfer valve		
* RPM indicator	* Hydraulic electric pump (nose wheel location)		
* Oil pressure switch	* Elevator trim tap		
Propeller governor	* Instrument drives		
* Flap actuator	* Camera drives		
* Slat actuator			
* Flap bell crank			
Inspection		**Inspection**	**Inspection**
Calendar		Calendar	Calendar
Repair		Repair	Repair
Overhaul		Overhaul	Overhaul
			CER

* Airframe Splines

As will be shown later, the majority of spline wear problems encountered in the field have been with interface splines that connect the engine or accessory gearbox to accessories such as starters, generators, hydraulic pumps, fuel pumps, etc. These splines all experience either continuous or frequent operation at substantial rotational speeds and torques. They also must contend with less favorable lubrication as a rule. Many of the other splines in the aircraft which do not exhibit serious wear problems are usually subjected to combinations of low speeds, light loads, and intermittent operation. Some of these enjoy very favorable lubrication.

II. FACTORS AFFECTING SPLINE LIFE

Toothed splines are used to transmit power or drive accessories, where space and weight are of paramount importance. Although many alternative means of drives can be cited and are indeed used in other situations, none can compare with splines in terms of compactness and light weight. Splines are relatively low in initial cost; but not necessarily in overall cost when maintenance and replacements are also considered.

Splines can and are normally expected to accommodate a small amount of misalignment, which may be the result of design, installation, or dynamic operating conditions. However, if the misalignment is large, then the resulting oscillatory, fretting-type of wear will be excessive. In the interests of reduced maintenance, extended life, and increased reliability, there is no question that special attention should be directed toward misalignment control. With adequate misalignment control through careful design and installation, the burden on material selection, lubricant selection, lubrication technique, other aspects of design details, and virtually all aspects of the maintenance process is greatly eased. Without it, all these others can only help to relieve a fundamentally difficult problem.

The factors which affect the life of spline connections may be divided into four broad categories: design, operating variables, lubrication, and installation and maintenance. These factors will be briefly considered in this chapter in general terms, and referred to again more specifically later when discussing the current practices. Although the problem of spline wear is certainly not new, much of the systematic information on spline wear and its mitigation in the open literature has been the work at SwRI in the past eight years. The SwRI results are briefly summarized in Appendix A, so as not to break the continuity of the text. However, frequent references will be made to it throughout this report.

A. Design

The most important group of factors affecting spine wear are those relating to design. The decisions made at the design stage affect nearly all of the other subsequent factors. Further, the cost of rectifying any poor design decisions may be very high once a design has been put into service.

1. Design Standards

Many of the design factors relating to aircraft splines are specified in such military standards as AND and MS. In addition, various industrial design standards such as SAE, AS, ANSI, and ISO are used. The standards of interest are related to the engine, accessory gearbox, accessories, and to other spline connections used throughout an aircraft. The main purpose of the standards is to provide a design criteria for the designer to insure proper operation of the mating spline connection. The major factors relating to design will be discussed briefly at this time. However, the adequacy or mutual compatibility of the existing standards—particularly AND and MS—will be discussed later when considering the current design practice.

2. Spline Geometry

Spline geometry, for the purpose of this report, is considered to include tooth form and proportions. Aircraft splines are generally of the involute form and have straight nonhelical teeth. Some smaller splines with straight-sided teeth were encountered in the survey; but the number of these was small compared to the number of splines with involute teeth. Most splines encountered had straight involute teeth; but some crowned splines are also used. Crowned splines are generally regarded to be more tolerant of misalignment and afford better access of lubricant to the tooth surface than do straight involute splines.

The combination of pitch diameter, number of teeth, and length of engagement should be such that the shear strength of the teeth will be equal to or greater than that of the shaft. The height of spline teeth is generally less than that of gears of corresponding tooth form and size. In aircraft splines, tooth height is generally in the range of 1/2 to 2/3 that of corresponding gear teeth, with 1/2 tooth height being predominant in later designs.

Three types of fits are used in splines: side fit, major diameter fit, and minor diameter fit. Side fit is called for in AND and MS standards; hence is the type most frequently encountered in aircraft splines.

The effect of a number of the geometry factors is discussed in Appendix A.

3. Hardness

The hardness of the male and female splines can be a very significant factor in the life of the spline connection. Splines are normally through-hardened or case-hardened depending upon the specifications in the design standards or the option of the spline or component manufacturer. Increasing the hardness of either the male or female spline will usually allow that part to operate longer than the softer mating spline. In selecting the hardness of the splines, particular attention should be given, among other factors, to the ease of of spline replacement.

4. Surface Texture

Surface texture can affect the rate of spline wear for several reasons. With rougher surfaces, stresses at prominent asperities may become high, promoting adhesive wear and possibly also fatigue failures. However, the rougher surfaces do have the advantage of providing greater grease reservoir capacity and numerous passageways for grease flow, thereby enhancing lubrication and wear life (Appendix A). Thus it is evident that optimum surface texture may exist for various combinations of lubricating and operating parameters. Surface texture encompasses both the average surface roughness and the details of the surface irregularities.

5. Materials

The selection of spline materials is a very important factor in the life of a spline connection (Appendix A). Since some spline wear is inevitable, consideration must be given in the material selection stage as to which splined part, the male or female, should receive the most wear. Various steels have been used rather extensively, but beryllium copper and titanium alloys are also used in some designs for aircraft components at the discretion of the designer. However, the AND and MS design standards do not specify spline materials.

6. Coatings

Spline wear may be pronouncedly or substantially reduced by the use of suitable metallic or plastic coatings on the spline teeth (Appendix A). Coatings are, however, not specified in the AND and MS design standards.

7. Misalignment

As already mentioned, misalignment is probably the basic cause of early spline failures. Misalignment of mating splines produces several adverse effects on the overall performance of the components involved. First, misalignment greatly accelerates spline wear, as it causes increased local contact stress and also relative sliding motion (Appendix A). Second, if the misalignment is too great with respect to the chordal clearance between the mating teeth, interference will result. Third, excessive misalignment may impose loads and stresses in addition to those resulting from the transmitted torque, which then result in overloading of bearings or some other parts. In general, however, even if the misalignment is not serious enough to cause tooth interference or other components from overloading, its detrimental effect on wear alone may be sufficient to warrant serious concern.

As emphasized earlier, adequate misalignment control eases the entire problem of spline failure and maintenance. Much should and can be done at the design stage to ensure adequate alignment in the original equipment and in the interchangeability of subsequent replacements.

B. Operating Variables

Spline connections can be subjected to a variety of operating variables including speed, torque, tooth engagement, temperature, environment, and contaminants. A significant change in any of these variables can affect the life of a spline connection.

1. Speed

In the majority of aircraft spline applications, the components and accessories are subjected to a variety of speed ranges. Increased speed would be expected to result in increased wear due to the increase in relative sliding motion between the tooth surfaces. Increased speed would also increase dynamic loads due to any system imbalance, resulting in increased tooth loading.

The operating speed range is normally not within the control of the designer. In a sense, the penalty of high operating speed must be accepted. However, for high-speed operation especially, special attention should be given other design details so as to give the spline a better chance for survival. These factors include, in particular, accurate alignment, reduced tooth loading, and careful component balancing.

2. Torque

Torque, like speed, is a design requirement imposed by the application and is not under the designer's control. However, a knowledge of the effect of torque on spline life can be very helpful. An increase in tooth loading has been found to accelerate spline wear (Appendix A). Thus, for a given spline design, an increase in the transmitted torque increases the tooth loading and accelerates spline wear. What is within the control of the designer is that, where a high imposed torque is required, he should be sure to so proportion the spline as to keep the tooth loading within acceptable limits. In high-torque applications, as in high-speed applications, special attention to design details may reap rich dividends.

3. Tooth Engagement

The engagement of a spline connection should be such that one of the splines is completely engaged with the mating spline. Partial engagement of mating splines will create a higher tooth loading situation, thereby accelerating wear in the spline connection. As worn spline parts are replaced on components, provisions should be made so that the same spline engagement is obtained in order to ensure that nearly the same tooth loading is present.

4. Temperature

Temperature effects can aggravate spline wear by (1) thermal displacements causing misalignments and interference, (2) high temperature promotes deterioration of the lubricant and deterioration of the elastomer seals which may be essential for lubricant retention, and (3) low temperature thickens the lubricant and thus impedes its flow. The thermal displacement problem is directly the responsibility of the designer. The other two problems influence lubricant and elastomer selection.

5. Environment

Aircraft splines may operate in air, oil, or fuel environments. In general, lubrication is most favorable and wear the least bothersome when the spline operates in the lubricating oil or hydraulic fluid (Appendix A). Since jet fuels are poor "lubricants", they do not provide much protection, and the more highly refined the fuel is, the less lubrication it provides (Appendix A).

By far the greatest number of splines used in an aircraft operate in the air environment. Such splines are normally lubricated with a grease, primarily in the interests of simplicity and convenience. Proper grease selection is important. The designer should also keep in mind that exposure of a grease-lubricated spline connection to fuel may negate the beneficial effect of some best spline greases (Appendix A). For such applications, it may be wise to consider other design or lubrication alternatives.

6. Contaminants

In greased splines especially, the wear debris generated from the wearing of mating spline teeth will usually remain within the spline connection. Such debris will be in the form of metallic particles and iron oxides, which generally accelerate wear (Appendix A). Other contaminants may include dust, salt water, fuel, etc., depending upon the application. Excessive exposure to such contaminants should be avoided by proper sealing.

In the event that the spline connection is not thoroughly cleaned between relubrication intervals, grease carryover containing particles and oxides is possible. This contamination carryover can indeed affect the life of the spline connection.

C. Lubrication

1. Mechanism of Spline Wear

As discussed in greater detail in Appendix A, the fretting type of wear process as experienced in splines comprises a period of negligible wear known as an "induction period", followed by a period of rapid wear in which the wear rate is essentially linear. The induction period has been established to be chemical in character and may be enhanced by use of suitable antioxidants or corrosion inhibitors. The rapid wear period is essentially mechanical in character, and the wear rate is influenced more by materials and surface treatments and the relative amount of sliding (i.e., misalignment or high speed) than by either the lubricant or the other operating variables. To minimize total wear, it is of course desirable to employ lubricants of long induction period.

Figure 2 portrays the behavior described. Case B in this figure shows the wear behavior in dry air without any lubricant present. In this case, wear commences immediately upon the start of oscillatory motion, and proceeds at a linear rate. Case A illustrates the behavior with a noninduction-period grease, which also gives immediate and a linear rate of wear, but the rate of wear is noticeably, though

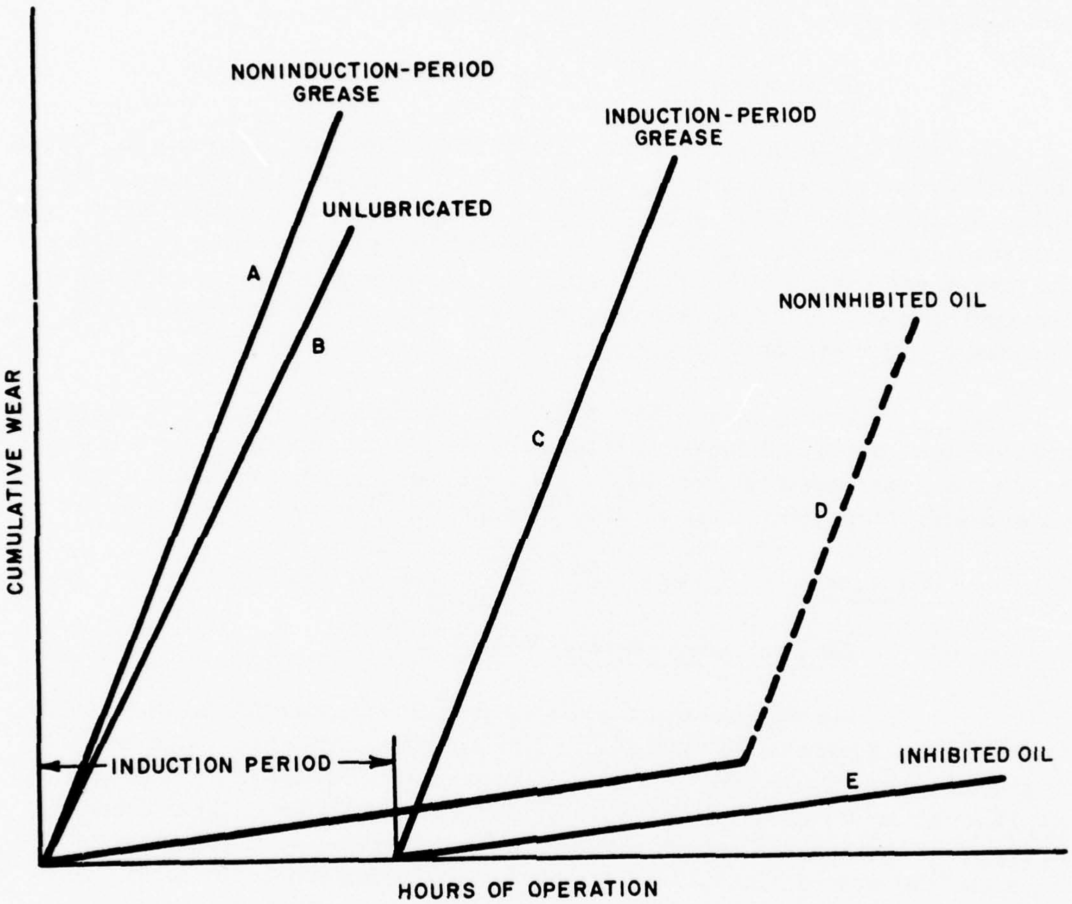

FIGURE 2. GENERAL BEHAVIOR OF SPLINE WEAR IN DRY AIR

only slightly, higher than the unlubricated case. This is because the grease tends to retain the wear debris in the contact zone, which oxidizes or partially oxidizes to form hard oxides and cause abrasive wear.

With an induction-period grease, as illustrated by Case C, there is first an induction period of negligible wear. After the chemical constituents in the fixed amount of grease are used up, there follows a period of rapid wear, with a wear rate similar to that of Case A (noninduction-period greases). It has been found that if at the end of the induction period, the used grease is removed and the splines cleaned and recharged with fresh induction-period grease, the period of negligible wear will repeat. In other words, with continued replenishments of fresh induction-period grease, negligible wear will continue to be obtained.

If the splines are lubricated with a fixed and limited amount of a noninhibited oil (no induction period), the wear behavior would be as illustrated by Case D. Without an induction period, wear commences immediately upon the start of relative motion. However, in this case, the wear rate, while also linear, is very low because the presence of the liquid tends to help carry the wear debris away from the contact zone. Futher, presence of oil tends to minimize the oxidation of the wear debris. However, after the liquid has been "pushed away" from the contact zone by the repeated oscillatory motion, there is no more lubricant present and hence a period of rapid wear ensues, much as in the unlubricated case.

If the fixed and limited amount of the liquid lubricant contains suitable additives to provide an induction period, then the behavior would be as shown by Case E. There will first be a period of negligible wear. After the chemical constituents in the oil are consumed, a period of appreciable wear will take place. The wear rate is similar to that of Case D since the liquid tends to carry the wear debris away from the wear zone and also minimizes wear debris oxidation. On the other hand, if the liquid supply is large, or if the oil lubrication is continuous, then negligible wear will continue.

Solid-film lubricants have been found to behave similarly to the unlubricated case (Case B). Solid films are generally very thin and provide almost no protection against wear under these conditions. However, the loose wear debris will move away from the contact zone, because there is no grease to retain them there.

2. <u>Lubricants</u>

Most aircraft splines operate in the air environment and they are usually grease-lubricated for convenience and system simplicity.

As mentioned in the preceding section, greases of long induction period are obviously desirable for such applications.

In some cases, a normally grease-lubricated spline may be exposed to fuel (for example, the spline which drives the fuel pump may be exposed to the fuel due to defective fuel-side seal), and the effect can be very detrimental. In such instances, if no other alternative is present, it may be wise to select a grease of less solubility to fuel so that the wear when exposed to fuel would be less excessive—by paying a penalty in accepting a shorter induction period.

As mentioned in the preceding section, liquid lubricants can greatly control spline wear. However, this method does introduce system complexity and weight problems, and must be weighed very carefully in the design stage as to its overall feasibility.

As mentioned in the preceding section, solid-film lubricants are not effective in spline applications.

3. Lubrication Methods

Aircraft spline connections are usually lubricated with a grease or liquid lubricant since solid-film lubricants have not proven to be very effective in mitigating spline wear (Appendix A). The lubricating methods used may be divided into three categories, namely: dry pad, mist, and wet pad. The dry pad spline connection can be operated with or without a grease, resulting in spline wear behavior similar to that illustrated in Case A, B, or C of Figure 2. The mist (oil mist) and wet pad are usually associated with the engine accessory gearbox splines and are oil lubricated, resulting in spline wear similar to Case D or E of Figure 2. It is evident that the lubrication method selected could control the effective life of a spline connection. The dry pad is usually the simplest method since no elaborate lubrication system is required, although it may not be as effective as mist or wet pad. In many cases, the location of the spline connection on the aircraft will dictate the type of lubricating method to be used in the interest of space and weight considerations.

4. Lubrication Interval

The interval of lubrication (or "relubrication", as it is frequently called) is of concern primarily with grease-lubricated splines. Ideally, it is desirable to replace the used grease in a spline with fresh grease before the induction period of the grease is used up. In any case, in critical spline connections, frequent relubrication must be considered good policy.

5. Accessibility for Relubrication

In the relubrication process, it is important to clean the spline connection thoroughly to prevent used grease and contaminant carryover. However, this may be more easily said than done, because the splines may not be readily accessible for cleaning. This aspect of the problem will be discussed further later. Suffice it to say here, accessibility is a problem that can be handled with foresight in the design stage. A number of alternatives, either to improve accessibility or to sidestep the problem, will be discussed later.

D. Installation and Maintenance

The practices employed during the installation and maintenance at various Navy maintenance levels can have an effect on the life of a spline connection. These include cleaning, relubrication, and alignment problems.

1. Operational Level (Squadron)

At the operational level performed at the squadrons, the general practice is to replace accessories such as fuel pumps, hydraulic pumps, starters, generators, etc. At this level individual splines are generally not replaced. In the event of spline failure for any cause, the entire component or accessory would be replaced and the defective unit sent to either an intermediate or depot level maintenance facility for rework.

One potential source of trouble may be encountered more frequently at the squadron level than elsewhere: During installation of heavy accessories, there is the danger of damage to the flange or piloting surface on the mounting pads, and shafts or splines may be bent or deformed at localized areas due to supporting the accessory weight on the spline shaft prior to engagement of the piloting surfaces and securing of clamping devices. Damages of the type just mentioned can result in increased spline misalignment and hence accelerate wear. The problem can be greatly reduced by the use of slings, hoists or other devices to support and guide the accessory into place.

Another factor of importance at the operational level is the cleaning and relubrication of splines whenever accessories are removed and replaced. If these two tasks are not performed carefully, wear debris and used grease may be carried over into the new spline connection. Female splines, by virtue of their design, are difficult to clean unless adequate brushes are used to remove the wear debris, oxides, and grease residue. Some female splines are rather long in

relation to the pitch diameter making it even more difficult to visually inspect and clean the spline teeth. Male splines are normally easier to inspect and should also be thoroughly cleaned prior to relubrication.

2. Intermediate Level (Squadron or Commercial)

Intermediate level maintenance is performed mostly at the squadron level, or by a commercial contractor. At the intermediate level of maintenance, accessories are disassembled, inspected, reworked if necessary, and then reassembled. Hence additional factors which may affect spline wear are present. Several factors relate to inspection practices. These include the type and magnitude of the wear rejection criteria applied to the splines and the methods of measuring spline wear.

Replacement factors include a variety of factors which can have significant effects on spline wear. Frequently, replicates of the original parts are not available and it is necessary to substitute new parts of different design, tolerances, or materials; or else the worn part may be reworked in some manner to restore it to a useable condition. Unless care is taken, the substitute parts or reworked parts may adversely contribute to tolerance stackups or misalignments, and may result in combinations of mating materials that are not compatible.

One practice in particular which can aggravate spline wear is the use of a worn spline with either a new spline or a worn spline. This practice can result in unusual tooth loadings both as to localized magnitude or location and may therefore accelerate wear. The practice results because replacement parts are either in short supply or are expensive, hence splines are reused so long as the wear rejection criteria are not exceeded. Other reasons for the practice are the fact that spline-connected components are often overhauled at different facilities. Many accessories such as starters, generators, hydraulic pumps, etc., are replaced as a unit at the operational level of maintenance. Thus at overhaul facilities where aircraft are nearly completely disassembled and reassembled, components are not matched up with the component with which they were originally connected. In other words, to ensure complete and compatible interchangeability, the allowable tolerances—particularly those having to do with misalignment or tooth interference—should be examined carefully.

3. Depot Level (NAVAIREWORKFAC or Commercial)

The depot level is the highest level of maintenance, which function is normally performed at a NAVAIRWORKFAC, but sometimes also by a commercial contractor. The work involves disassembly,

inspection, and rebuilding of accessories, components, and complete aircraft. Hence, the maintenance factors encountered include all of those encountered at the lower levels of maintenance. In addition, at depot level, considerable reworking of parts may be performed, especially when parts are in short supply. Occasionally, new parts are manufactured at the NAVAIREWORKFAC(s).

4. New and Used Splines

The widely used maintenance practice of reusing splines in combination with new or other used splines may have an adverse effect on the life of both splines involved in a connection. When worn and new spline surfaces come into contact, the load may be borne initially by a relatively small area, thus resulting in excessive contact pressures and a high rate of wear. During the period of high wear rate, wear debris are formed and these in turn may serve as abrasives to promote additional wear. Where two new, properly shaped, splined surfaces come into contact, the load is more uniformly distributed and, also, the amount of wear necessary to provide good conformity is much less than is the case where an unworn and a worn spline surface are in contact. The reuse of slightly worn splines is dictated by economic considerations; but indiscriminate use of worn splines may not be as economical as it appears at first glance.

Even greater wear acceleration may result if the reused worn splines are improperly cleaned thus permitting carryover of used grease and wear debris into the new spline connection.

5. Cleaning and Lubrication

The essential lubrication-related tasks in the installation of a spline connection consist of assuring that both splines are clean; that all closures, seals and other lubricant retention devices are properly installed; and that lubricant of the proper type and amount is applied. It would be desirable if the same lubricant is used at installation and at subsequent relubrications.

The lubrication-related tasks are equally important in both installation and maintenance operations. Where components are removed or disassembled sufficiently to permit cleaning of the splines, the tasks are the same as at the installation. However, in many cases, splines are relubricated in locations where cleaning is more difficult than at installation or overhaul facilities.

As mentioned earlier, the accessibility of one or both of the splines may hamper the cleaning and relubrication. Small wear debris particles left between the male and female spline teeth can shorten the effective life of the spline connection.

6. Misalignment

The importance of obtaining the best possible alignment between two mating splines has been repeatedly emphasized in the preceding paragraphs. The alignment may be described in terms of lateral alignment and angular alignment. Lateral alignment refers to the concentricity between the mating splines. Angular alignment refers to the angular orientation between the mating splines. Excessive misalignment in either sense will affect the tooth loading, thus leading to excessive wear, pitting, or even fatigue breakage.

As mentioned previously, design plays an important role in controlling misalignment. The design tolerances should be such as to avoid excessive stackup errors. No effort should be spared at the design stage to ensure that each spline is lined up with the component to which it is attached, and further to ensure that the two mating splines are lined up when the two components are put together at least in the initial installation.

Misalignment becomes a problem in the maintenance sequence mainly because of the necessity of interchanging parts or accessories. Since servicing of different accessories or components currently fall under the jurisdiction of different service groups or organizations, the best that each such organization can do is to see that the spline attached to the accessory or component is properly aligned. Even so, the method of measuring misalignment is often inadequate, even at the highest maintenance level, to ensure that a proper job is done. Moreover, as the jurisdiction for different components is currently divided, there is no real assurance that two separately serviced components, when assembled together, will result in satisfactory alignment of the mating splines.

III. INFORMATION SOURCES

A. Visits

Visits were made to seven Naval Air Rework Facilities, two Air Force Depots, one Army Aeronautical Depot Maintenance Center, two commercial airlines, two airframe manufacturers, three accessory manufacturers, two lubricant manufacturers (in addition, representatives of one lubricant manufacturer visited SwRI), and two Naval Air Stations as shown in Table 2. A visit was also made to NADC early in the program. Two visits were made to NASC with the last one being an informal presentation to Navy, Air Force, and Army personnel summarizing the results and recommendations of the survey program.

At each place visited, personnel cognizant of aircraft spline wear problems were interviewed to collect the necessary information. These included engineers, technicians, and shop personnel. For example, at the NAVAIREWORKFAC(s), personnel were contacted in the Aeronautical Engineering and Quality Assurance Departments. During the course of a visit, shop areas were toured and appropriate shop foremen and personnel were contacted.

Nearly all of the major spline problem areas were verified with the Quality Assurance Department. This department, along with the Production Planning Group, provided information on the replacement rate or usage of the specific spline components. This information can be obtained with the IR/6R Usage Summary entitled "Eight Quarters Through Fourth Quarter, FY 1970". This is a computerized listing of the usage of individual component parts.

Some NAVAIREWORKFAC(s) maintained a Master Usage File (MUSF) for aircraft parts tabulated for a one-year period. In the majority of cases, the usage or replacement factor was based on these computer listings; however, in some cases, it was estimated by NAVAIREWORFAC personnel.

B. Survey Forms

A large portion of the information was collected by means of three questionnaire forms.

1. Aircraft Spline Survey Form

The most important of these, the Aircraft Spline Survey Form illustrated in Table 3, was used at all facilities except the lubricant

TABLE 2. FACILITIES VISITED DURING SURVEY

Type of Facility	Facility	No. of Days	Visit Dates
Naval Air Rework Facility	Alameda	3	25-27 Jan 1971
	Cherry Point	2	25-26 Feb 1971
	Jacksonville	3	29-30 Sep, 1 Oct 1970
	Norfolk	3	2, 5, 6 Oct 1970
	North Island	3	19-21 Jan 1971
	Pensacola	3	12-14 Aug 1970
	Quonset Point	4	7-9, 12 Oct 1970
Air Force	Kelly	3	13 Jul, 18 Aug, 25 Nov 1970
	Tinker	3	17-19 Nov 1970
Army	ARADMAC	3	27-28 Aug, 16 Nov 1970
Airlines	American	1	20 Nov 1970
	United	1	1 Feb 1971
Spline and Accessory Manufacturer	AiResearch	1	18 Jan 1971
	Bendix	1	22 Jul 1970
	Sundstrand	1	30 Mar 1971
Navy	NADC	1	24 Jul 1970
	NASC	2	21 May 1970, 17 June 1971
NAS	Corpus Christi	1	18 Sep 1970
	Kingsville	1	17 Sep 1970
Airframe Manufacturer	Lockheed	1	22 Jan 1971
	Boeing	1	2 Feb 1971
Lubricant Manufacturer	Chevron	1	29 Jan 71
	Shell*	1	4 Feb 1971
	Texaco	1	23 Jul 1970

*Shell representatives visited SwRI

TABLE 3. AIRCRAFT SPLINE SURVEY FORM

Contact: ______________________
Title: ______________________
Organization: ______________________
____
Telephone: ______________________
Date Completed: ______________________

Survey by M. L. Valtierra
Southwest Research Institute
8500 Culebra Road
San Antonio, Texas 78228
Phone: 512---684-2000

Aircraft ______________________ Engine ______________________

	FAILED OR REJECTED SPLINE CONNECTIONS	
Accessory Name		
Accessory Part Number		
Accessory Manufacturer		
Spline Location		

Spline Description	Male	Female
Design Standard		
Part Number		
Drawing Number		
Manufacturer		
Diametral Pitch		
Number of Teeth		
Spline Length, in.		
Pitch Diameter, in.		
Pressure Angle, deg.		
Tooth Form		
Class of Fit		
Type of Fit		
Material		
Heat Treatment		
Core Hardness, R_c		
Case Hardness, R_c		
Case Thickness, in.		
Machining Method		
Coating and Thickness		
Surface Roughness		

Operating Conditions		
Constant Speed, rpm		
Variable Speed Range, rpm		
Angular Misalignment, deg.		
Lateral Misalignment, in.		
Axial Engagement, %		
Operating Torque Range, in-lb		
Spline Temperature Range, °F		
Spline Environment, Air, Fuel, etc.		
Salt Water Exposure		

TABLE 3. AIRCRAFT SPLINE SURVEY FORM (Cont'd)

Lubrication	Male	Female
Applicable Lub. Specification		
Lubricant		
Lubricant Supplier		
Lubrication Interval, hr.		
Lubricant Flow Rate		
Lubricating Method		

Spline Failure History		
Usage; Replacement Rate, %		
Accessory O. H. Period, hr.		
Spline O. H. Period, hr.		
Accessory Failures per yr.		
Accessory Mean Life, hr.		
Spline Failures (UR) per yr.		
Spline Mean Life, hr.		
Spline Failure Category		
Tooth Wear		
Wear Debris, Describe		
Tooth Fracture		
Shaft Fracture		
Allowable Spline Wear, in.	O. H. ;Sq.	O. H. ;Sq.
Wear Measuring Equipment		
Corrective Recommendations		

Corrective Recommendations		
Current		
Proposed		

Items Supplied to SwRI		
Accessory Assy. Drawing		
Spline Drawing		
Spline Lub. Instructions		
Spline Inspection Instructions		
Worn Splines		

Comments

manufacturers. This form identifies the person and organization reporting the spline wear problem, the aircraft, spline location, details of spline parameters such as geometry, material, hardness, surface finish, etc.; operating conditions, lubrication particulars, spline failure history including replacement rate, wear description, spline wear rejection criteria, and wear measuring equipment; and current and proposed methods for correcting or mitigating spline wear. Wherever possible, the foregoing information was collected at the time of the visit. However, in many cases, all of the information was not readily available and was collected by means of subsequent communications. For example, in many cases, drawings of problem splines were provided by the personnel visited. Spline details were then extracted from the drawings by SwRI personnel. In quite a few cases, only the drawing numbers were provided at the time of the visit and the drawings were obtained through other sources including DCASO, San Antonio; NADC, Philadelphia; Kelly AFB, San Antonio; and AVSCOM, St. Louis.

Information on operating conditions and lubricating particulars was generally obtained from the cognizant engineering personnel and in a few cases from appropriate documents such as NAVAIR Specifications, Air Force T.O.(s), Military Standards, Overhaul Manuals, etc.

2. Lubricant Manufacturers Survey Form

The lubricant manufacturers survey form, shown in Table 4, was used in the meetings with personnel of lubricant manufacturers. The information requested in this three-part form consisted of (a) general recommendations as to spline design and materials, surface finish, and lubricating practices that would reduce spline wear, and test methods for evaluating spline lubricants; (b) description of current spline lubricants; (c) suggested components of spline grease lubricants. As will be evident in the section on Lubrication, this form proved to be too detailed. For proprietary and other reasons, only one of the lubricant manufacturers contacted completed this form.

3. Squadron Maintenance Practices Survey Form

Early in the survey, it became evident that one source of wear aggravation might be incomplete cleaning of the splines when accessories were replaced in the field. Unless carefully cleaned, old grease and/or wear debris could be introduced into the new connection, thus greatly accelerating wear. In order to obtain additional information

TABLE 4. LUBRICANT MANUFACTURERS SURVEY FORM

A. General Recommendations
B. Current Lubricants Suitable for Splines
C. Suggested Components of Spline Grease Lubricant

Contact:____________________________
Title:______________________________
Organization:_______________________
Address:___________________________
____
Telephone:_________________________
Date Completed:_____________________

Survey by M. L. Valtierra
Southwest Research Institute
8500 Culebra Road
San Antonio, Texas 78228
Phone: 512---684-2000

A. GENERAL RECOMMENDATIONS

1. Spline design recommendations that would enhance lubricant effectiveness:

2. Lubrication techniques or practices that would improve spline performance:

3. Importance of spline materials:

4. Importance of material hardness:

TABLE 4. LUBRICANT MANUFACTURERS SURVEY FORM (Cont'd)

5. Importance of surface finish:

6. Effectiveness of spline coatings (platings, reaction films, polymers, bonded solid lubricants) and/or compatibility of the coatings with spline lubricants:

7. Importance of clearance:

8. Effects of contaminants (dust, sea water, chemicals, others):

9. Test methods used to evaluate spline lubricants:

10. What spline data and operating conditions do you require in order to formulate a grease for a particular application:

11. Advantages or disadvantages of oil lubrication of splines:

TABLE 4. LUBRICANT MANUFACTURERS SURVEY FORM (Cont'd)

B. CURRENT LUBRICANTS SUITABLE FOR SPLINES

Lubricant Description	Lubricant Data	
Manufacturer's Identification		
Type (Grease, Oil, Solid film, etc)		
Military or Other Specifications		
Base Stock		
Thickener Type		
Additives		
Other Components		
Lubricant Properties		
API Gravity		
Flash Point		
Fire Point		
Pour Point		
Viscosity at 100°F		
Viscosity at 210°F		
Viscosity Index		
Acid No.		
Base No.		
Interfacial Tension		
Copper Corrosion		
Steel Corrosion		
Dropping Point, (min)		
Worked Penetration		
Bomb Oxidation, Pressure Drop in 100 hrs, in psi (max)		
Water Resistance at 100°F, percent grease loss by wt (max)		

TABLE 4. LUBRICANT MANUFACTURERS SURVEY FORM (Cont'd)

Lubricant Properties - (Cont'd)	Lubricant Data	
Evaporation at 250°F (max)		
Oil Separation at 210°F (max)		
Low Temperature Torque (indicate temp.)		
Starting Torque, g-cm		
Running Torque, g-cm		
Load Wear Index (min)		
Worked Stability (max)		
High Temperature Performance at 250°F (min)		
Run on Steel Wear		
Rust Preventive Properties		
Spline Wear Performance		
Test Apparatus		
Wear Performance in Air, describe		
Wear Performance in Fuel, describe		

TABLE 4. LUBRICANT MANUFACTURERS SURVEY FORM (Cont'd)

C. SUGGESTED COMPONENTS OF SPLINE GREASE LUBRICANT

Operating Conditions:	In Air		In Fuel	
Speed, rpm	2000	4000	2000	4000
Contact, Stress, psi	1000	5000	1000	5000
Temperature, °F	200	300	200	200

Check Those Components You Consider Necessary For A Grease Used To Lubricate Splines Under The Indicated Conditions

Lubricant Component				
Base Stock				
Thickening Agent				
Oxidation-Inhibitor				
Corrosion Inhibitor				
Detergent				
Dispersant				
Rust Inhibitor				
Oiliness Agent				
Extreme Pressure (EP)........				
Tackiness Agent				
Antiwear				
Solid Lubricants (fillers).......				
Metal Deactivators				
Alkaline Agent				

with regard to this problem, the Squadron Maintenance Practices Form (see Table 5) was prepared and submitted to the Atlantic NAVAIREWORKFAC Representative who in turn submitted this to COMNAVAIRLANT and COMNAVAIRPAC for approval and subsequent distribution. However, only one set of reports were received from the Norfolk Naval Air Station.

C. Supplementary Information

In addition to the information collected by means of the survey forms just described, considerable information was obtained from other sources as follows:

Spline Drawings
NAVAIR & T. O. Specs.
Tech. Manuals
Field Failure Reports
Local Engineering Specs.
Engineering Change Proposals
Engineering Program Notices
P. P. Changes & Bulletins
Technical Reports
Component Improvement Programs
Development Programs

TABLE 5. SQUADRON MAINTENANCE PRACTICES SURVEY FORM

Please complete the form for the aircraft in largest quantity in your squadron.

Name: ____________ Aircraft: ____________
Title: ____________ Engine: ____________
Organization: ____________

Return form to: Mr. M. L. Valtierra
Southwest Research Institute
8500 Culebra Road
San Antonio, Texas 78228

QUESTION ↓ ACCESSORY →	Constant Speed Drive	Generator	Starter	Hydraulic Pump	Fuel Pump
Do you remove and replace the accessory (Yes or No)?					
Do you replace any splines between the accessory and mating component (Yes or No)?					
Before the accessory is replaced, how is female spline on the major component cleaned? (Explain).					
What document specifies spline cleaning instructions (NAVAIR, T.O., etc.)?					
What cleaning compounds or solvents are used in cleaning splines (MIL spec., FSN)?					
How often is the splined connection between the accessory and mating component lubricated (Hrs)?					
What document gives lubrication instructions (NAVAIR, T.O., etc.)?					
What spline lubricant do you use (MIL spec, FSN, and/or Mfg. P/N)?					
How is lubricant applied? (Explain).					

IV. MAINTENANCE FUNCTIONS

A. Facility Operation

A brief description of the operation of the various facilities visited follows:

1. Navy

As mentioned in Chapter II, the maintenance function in the Navy is performed at three levels: the operational (squadron) level, the intermediate (squadron or commercial) level, and the depot (NAVAIREWORKFAC or commercial) level.

Typical of the squadron operation is illustrated by the operation of Corpus Christi and Kingsville Naval Air Stations visited. Available at the Corpus Christi Naval Air Station is a CERFAC, which is the highest level of maintenance within the intermediate classification and is concerned with both hot and cold portions of the engine. There are four training squadrons at Corpus Christi: one employing T-29 aircraft and three employing TS-2A aircraft. Visits to Squadrons VT-27 and VT-29 revealed no existing spline problems on the aircraft at the organizational level of maintenance. Squadron VT-27 was having difficulty in obtaining the proper grease and was thus using MIL-G-7711 for spline lubrication. The view was also expressed that spline wear could be greatly reduced if the splines were carefully cleaned and regreased each time the coupling was disassembled. From 600 to 900 hours were obtained on fuel pumps (Pesco, Lear, Thompson). Seal failures were the principal cause for replacing these pumps, not excessive spline wear.

The AMD at Kingsville Naval Air Station supports the squadrons at Kingsville, repairing accessories to make them ready for issue, at which time the accessories are returned to supply. Kingsville also performs quick engine changes; but does not overhaul engines, which are usually sent to the CERFAC at Corpus Christi or else to one of the NAVAIREWORKFAC(s).

The NAVAIREWORKFAC(s) are the highest level of aircraft maintenance in the Navy. These Facilities disassemble, inspect, repair, rework, and restore all components of aircraft to a usable state. Each NAVAIREWORKFAC has certain aircraft or aircraft components which it reworks. There is some overlapping of responsibilities, that is, a given aircraft or component may be

reworked at more than one NAVAIREWORKFAC. Also, the NAVAIREWORKFAC(s) may authorize intermediate level maintenance facilities or commercial facilities to rework certain components.

During visits to the NAVAIREWORKFAC(s), the principal contacts were with personnel of the Airframe, Powerplant, Aircraft Accessories, Engine Accessories, Avionics, and Materials Laboratory divisions of the Department of Aeronautical Engineering and also with personnel of the Quality Assurance Department. Also, at each NAVAIREWORKFAC, the shop areas pertinent to the aircraft spline problems were visited and it was possible to observe maintenance operation and to talk with shop personnel cognizant of the spline problems.

2. Air Force

The organization structure at the Air Force Depots (Kelly and Tinker Air Force Bases) is essentially the same. The principal contacts at each base were personnel in the Service Engineering Division of the Directorate of Material Management. These divisions are divided into nine branches. Detailed information regarding spline wear problems was obtained principally from contacts in the Mechanical, Propulsion, and Electronics Branches.

3. ARADMAC

The Army Aeronautical Depot Maintenance Center (ARADMAC) is involved in sustaining second and third generation helicopters, and its principal role is reclaiming these helicopters. At ARADMAC, personnel were contacted in the following branches: Airframe, Accessories, Power Plant, Special Projects, and Technical Data Cataloging and Standardization Branch of the Army Systems Command Engineering Support Division. The branch chiefs were contacted first, and detailed information regarding specific information was provided by engineers in the Accessories Branch (the only branch reporting spline wear problems). Those shop areas related to the problem areas were also visited, and supplementary information was obtained from the shop foremen.

4. Commercial Airlines

The American Airlines Maintenance and Engineering Center at Tulsa, Oklahoma, has the responsibility for maintaining 707, 727, 747, and BAC-400 commercial aircraft. The general

operational philosophy is to condition, monitor, and maintain. Each aircraft receives Major Base Checks at Tulsa, and Field Base Checks at various airports. Personnel were contacted in Aircraft Systems Engineering, Power Plant, Engine Accessories, and Materials Laboratory.

Personnel at American Airlines advised that they were not aware of any current spline problem areas. Some problems had existed in the past; however, they were remedied by various means, including correcting misalignment, grease retention boot, better lubricants, and careful maintenance.

The United Airlines Maintenance Base at San Francisco, California, has the responsibility for maintenance of the DC-8, 720, 727, 737, and 747 commercial aircraft. Personnel in the Engineering Standards and Methods Section were contacted. Prior to the visit they had collected spline wear and related information from personnel cognizant of hydraulics, engine, engine accessories, and airframes. According to United personnel, there is no particular time that an aircraft engine comes in and is completely overhauled. At approximately 6000 hours (excluding the JT-9D engine on the 747), the engine goes through an engine heavy maintenance (EHM), at which time it is reworked at the "burner section" only. Information was collected pertaining to three spline wear problems, greases and other lubricants used by United Airlines, generator spline lubricants used by ten different airlines, wet pads for new aircraft, spline wear measuring devices, and information relating to overhaul, check, and engine heavy maintenance periods on current UAL aircraft.

5. Air Frame Manufacturers

The Boeing Company is engaged primarily in building aircraft for commercial airlines. At present, they are not fabricating any Air Force or Navy aircraft. Also, no engines are overhauled at the Seattle location. The engine package is furnished to Boeing by the engine manufacturer. The alignment of splines, drive pads, and accessories such as starters, generators, and hydraulic pumps is not checked by Boeing. The aircraft manufacturer depends upon the manufacturer of the gearbox and the individual accessories for the correct alignment of the individual accessories.

Boeing personnel were contacted in the following areas: structures technology, materials, engine system reliability, design standards, mechanism design, and bearings. No specific spline wear problems were collected at Boeing; however, related information was obtained on the 1969 Aerospace Fluid Power Conference, spline design

specifications, airline versus Navy maintenance, spline lubrication, wet spline connections, 737 and 747 flap problem areas, and hydraulic pumps.

The primary function of the Lockheed Aircraft Corporation is to supply a completed aircraft to the customer. The fuselage, wings, and tail section are designed and build in accordance with Lockheed's specifications. The power plant is provided by an engine manufacturer in accordance with Lockheed's drawing envelopes. In most cases, Rohr Aircraft of Chula Vista, California, or perhaps Allison Aircraft Division of General Motors will usually manufacture the gearbox and obtain the accessories from various accessory manufacturers. In the design of the gearbox pad configurations, Rohr or Allison will utilize the design requirements set forth in the AND standards. The engine manufacturer will coordinate with the accessory manufacturers to assure that the spline connections are properly made for the various accessories. According to Lockheed personnel, the alignment of accessory drive pade, accessory flanges, and splines is not checked by Lockheed.

No information on specific spline problems was collected at Lockheed; however, related information was obtained on P-3 aircraft starter, generator, engine driven compressor, hydraulic pump, AH-56 helicopter transmission, AH-56 helicopter GE T64 engine, Allison CIP, T-56A-14 engine, gearbox, and interface spline design, S-3A new Navy aircraft, and S-3A wet spline designs.

6. Component Manufacturers

The Fluid Power Division of Bendix Corporation, Utica, New York, manufacturers three types of components involving spline connections to engine or gearbox; these are turbine starters, hydraulic pumps, and shaft power. The Bendix starters attach directly to the engine gearbox, range in output from 25 to 1200 hp, and are powered by either a fuel-air burner or high pressure air. Starters for military applications use spline connections manufactured in accordance with AND 20002. Personnel concerned with shaft power indicated they had no current spline wear problems.

Bendix personnel expressed the opinion that since the AND standards dictate the design, they do not have sufficient contol over the design of the male and female spline connections. Furthermore, because of the interface spline situation, what control they do

have over design parameters can be exercised on only one side of the spline connection, that is, with the accessory.

AiResearch Manufacturing Company located at Phoenix, Arizona, produces aircraft components of three different categories: propulsion engines; auxiliary engine systems which include gas turbine power and gas turbine compressor power units; and control systems which include aircraft valves, flap actuators, constant speed drives, wheel lowering systems, and thrust reversers. Current research and development programs include internal spline connections for fuel pumps.

B. Technical Details

During the course of the program, informal trip reports were submitted to NADC regarding information collected during the visits. These letter reports served as the informal reports required by the work statement; but will not be presented here in their original form in the interest of space.

A summary of spline wear research conducted at SwRI in the past eight years is presented in Appendix A. This appendix includes information on the mechanism of spline wear with data on the effects of greases, solid-films, fuels, misalignment, spline tooth load, surface roughness, tooth pitch, tooth crown, spline materials, plastic coatings, and metallic coatings.

A summary of all aircraft spline survey results are given in Appendix B. Included is detailed information relating to spline problem areas and some trouble-free spline connections reported by Navy and other organizations. Also included is information on spline history, wear measurement, rejection criteria, and corrective recommendations by the Navy and other organizations.

Appendix C summarizes the detailed information provided by the lubricant manufacturers contacted, including general recommendations, current greases recommended for spline operation, and suggested components for spline greases.

Appendix D provides information on the squadron maintenance practices forms received relating to the following aircraft: E-2A, E-2B, H-46, H-3, and F-4-B/-J.

Appendix E summarizes the status of current improvement programs on the following engines: JT-3D, JT-8D, JT-9D, J-48, J-57, J-65, J-71, J-79, J-85, R-1820, TF-39, T-53, T-56, T-58, and T-76.

Information is also included on the self-aligning 30 kva CSD, and the SST shaft power.

Finally, recommendations submitted to NASC by SwRI during the course of this program are reproduced in Appendix F. These are related to misalignment of interface spline connections, improved liaison between Navy organizations, and pitting damage on the upper spline connections on the main rotor mast on the UH-1 helicopters.

In addition to these detailed information, all relevant material has been integrated and discussed in appropriate portions in the main body of this report.

V. AIRCRAFT SPLINE FAILURE PROBLEM AREAS

A. Overall

A total of 91 spline problem areas were identified and are presented in Table 6 by problem area and the facility at which the problem was reported. The table includes reports from all spline users and manufacturers contacted, except the two Naval Air Stations which did not report.

The spline problem areas identified by Naval Air Rework Facilities personnel are associated with 40 and 70 percent of the Navy's fixed and rotary wing aircraft types, respectively. They represent 45 percent of the Navy's aircraft types, based on the 3M aircraft listing which includes essentially all of the active aircraft.

The greatest number of spline problem areas is associated with generators and alternators (16), fuel pumps (15—including 8 interface spline problems and 7 spline problems inside the fuel pump), CSD units (11—including 9 interface spline problems and 2 spline problems inside the CSD), followed by hydraulic pumps (10), and starters (10). These specific problem areas affect, as mentioned above, 45 percent of of the Navy's aircraft.

Further examination of Table 6 indicates that the major spline problem areas are related to the interface splines associated with aircraft engine accessory gearbox and specific accessories.

B. Fixed Wing Aircraft

As previously mentioned 40 percent of the spline problems encountered in this survey pertain to fixed wing aircraft, with the majority relating to interface spline connections at the engine gearbox accessory location. These problems will be discussed later under the particular accessory problem area.

Splines located in the airframe generally exhibited minimal to moderate wear. These splines are used in applications as noted by asterisks in Table 1. The majority are grease-lubricated and experience intermittent, light to medium loads. Some may be used to operate within a few degrees of rotation, while others may be designed to transmit loads having no relative motion between the mating splines (or serrations) as in a flap bell crank. Many small splines are located within instruments and camera drives transmitting very little power at relatively low speeds, and are not considered to be spline problem areas.

TABLE 6. SUMMARY OF FIXED AND ROTARY WING INTERFACE SPLINE FAILURE PROBLEM AREAS

	NAVAIREWORKFAC							Air Force		Army	Commercial Airlines		Accessory Manufacturers			
	Alameda	Cherry Pt.	Jacksonville	Norfolk	North Island	Pensacola	Quonset Pt.	Kelly	Tinker	ARADMAC	American	United	AiResearch	Bendix	Sundstrand	TOTAL
ENGINE																
Compressor Section			1					2								3
Scavenge Pump					1											1
ENGINE ACCESSORIES																
Engine to Gearbox					1•											1
*Engine to Shaft Power								2								2
*Shaft Power to Gearbox								2								2
*Shaft Power to CSD					1		1									2
AIRCRAFT ACCESSORIES																
*CSD	1		1		2		2		2							8
CSD-Internal									2							2
*CSDS				1												1
Fuel Control		1°														1
Fuel Pump		2			1, 1•			3	1							8
Fuel Pump-Internal	1	1	1		2•				1				1			7
*Generator-Alternator		1•, 1°, 1•°		1	2•	4	1•	3		1•		1				16
*Hydraulic Pump			2		4•	2	1•		1•							10
*Oil Pump					1•		1•									2
Oil Pump-Hydraulic Pump							2, 1•									3
*Starter, Air				1					1							2
*Starter, Electric	1		1		2•	1										5
*Starter-Generator										3•						3
MISCELLANEOUS																
Aux. Power Unit-Internal	1°												2°			3
*Engine-Shaft-Transmission										3•						3
*Main Rotor Mast										3•						3
*90° Tail Shaft										1•						1
*Propeller Hub	1															1
*Shaft to 42° Gearbox										1•						1
TOTAL	5	7	6	3	18	7	9	12	8	12		1	3			91

*Generally Interface Splines
•Helicopter
oAPU

1. Flaps and Slats

Perhaps the most heavily loaded noninterface spline connections are those utilized to operate the trailing edge flaps and the leading edge flaps called slats. The A-6 aircraft, for example, utilized a "track system" employing several gearboxes located within each of the wings. In between the gearboxes, various lengths of torque rods are connected to screw actuators by means of spline connections and universal joints to provide operation of the flaps and slats. There are a considerable number of splines in this area with the majority of the connections being grease lubricated.

Some aircraft manufacturers utilize alternate means for controlling flaps and slats by the use of cables and pulleys thereby eliminating a large number of spline connections. Others use a hinge and hydraulic system for operation of the flaps and slats.

American Airlines engineers reported no problems with 707, 727, and 747 aircraft which all utilize spline connections on the trailing edge flap. The flaps are actuated by means of electric motor driven "screw jacks". The 707 and 727 utilize a hydraulic cylinder on the leading-edge slat without spline connections while the 747 utilizes a pneumatic gearbox rack and track system.

Information obtained from The Boeing Company indicated a severe spline wear problem on the flap drive system at some locations between the torque rods and gearbox spline connections on the 737 and 747 aircraft. This spline connection is normally overhauled at 12,000 flight hours with periodic lubrication after approximately 6,000 flight hours using a MIL-G-23827 grease. Engineers felt that the problem had been solved in the 737 aircraft by improving alignment between the mating parts; however, the problem appears to still be present in the 747 aircraft. The base material of both of the spline connections was reported to be AISI 4340 steel for the uncrowned splines. Test stand results indicate that by coating the male and female splines with a proprietary gas nitride coating used with grease reduced wear for splines operating with a misalignment of 3 degrees.

2. Propeller Hub (Alameda)

Only one spline problem was reported relating to propeller hubs (Survey Form No. 208). The variable pitch propeller is used on a T-56-A8 engine on an E-2/C-2 aircraft, and splines are used in varying the propeller pitch. The spline connection rotates up to 90 degrees, depending upon the amount of pitch selected. It is suspected that the

subsequent propeller hub cracking is due to some type of fatigue failure attributed to overstressing of the connection. Worn splines were unavailable for examination.

C. Rotary Wing Aircraft

Approximately 15 percent of Navy aircraft types are helicopters. Seventy percent of the major spline problem areas reported in this survey are related to helicopter dry pad designs. The majority of these problems are located at the interface connections on combining gearboxes or transmissions and will be discussed under the specific accessory.

Spline problems located in areas other than the gearbox-accessory area include the ones listed below:

Aircraft	Engine	Survey Form No.	Facility
UH-1B, UH-1C UH-1D, UH-1E UH-1F UH-1H	T-53	135, 146, 147	ARADMAC
UH-1	T-53	145	ARADMAC
UH-1A, UH-1B, UH-1C, UH-1D	T-53	142	ARADMAC
CH-47	T-55	136, 137	ARADMAC
UH-1	T-53	144	ARADMAC
UH-53	T-64	239	North Island

1. Main Rotor Mast (ARADMAC)

The main rotor mast (Bell P/N 204-011-450) used on UH-1B, C, D, E, F, and H helicopters is reported by ARADMAC to require 50 percent replacement due to pitting damage experienced on the three upper spline connections, i.e., splines A, B, and C shown in Figure 3 (Survey Form Nos. 135, 146, 147). Each main rotor mast costs approximately $590, exclusive of labor cost. This main rotor mast is used on a vast majority of the helicopters overhauled at ARADMAC; in addition, similar pitting problems have been experienced

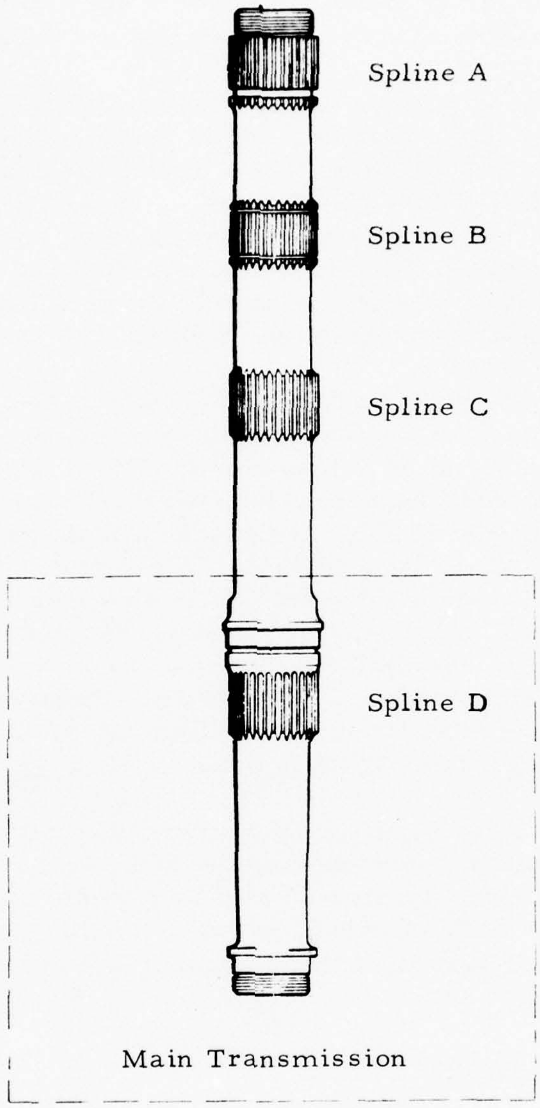

FIGURE 3. LOCATION OF SPLINES ON MAIN ROTOR MAST OF UH-1 SERIES HELICOPTERS

on Bell P/Ns 204-010-410 and 209-010-450 which are used on other UH-1 and AH-1 series helicopters. Spline D located in the transmission is oil-lubricated and has not been a serious maintenance problem.

The main rotor mast is fabricated of AISI 4340 (AMS 6415) steel, and the splines are not plated or coated by the manufacturer. During overhauls at ARADMAC, spline B is cadmium-plated in accordance with SEO No. UH-1-TO 211B. Splines A, B, and C located outside the transmission have shown pitting damage, with spline B exhibiting the greatest damage. Splines inspected at ARADMAC are rejected when the pit depth exceeds 0.010 inch as measured by a needle-pointed dial indicator. Pits of less depth are removed by blasting with dry glass beads.

During overhauls at ARADMAC, a MIL-C-11796 corrosion-preventive compound (only) is applied to splines A and B, while a MIL-G-25537 grease is applied to spline C in accordance with Chapter 8, Main and Tail Rotor Groups, and Chapter 2, Lubrication Instructions, respectively, of TM 55-1520-210-20. This technical manual specifies that splines A and B be recoated with a MIL-C-11796 corrosion-preventive compound whenever the main mast assembly is overhauled. The main rotor mast assembly has an 1100-hr overhaul period, but can be overhauled more frequently whenever it has been run at excessive speed. TM 55-1520-210-20 also specifies in-service relubrication of Spline C with a MIL-G-25537 grease at 100-hr intervals. These instructions specify hand-application of the grease, which is not a difficult operation.

In this instance, it should be noted that neither the MIL-C-11796 corrosion-preventive compound nor the MIL-G-25337 grease is a good spline lubricant. Consideration should be given to replacing them with a MIL-G-21164 or a MIL-G-81322 grease. Further, it is believed that more frequent relubrication of these problem splines should be considered.

2. <u>Shaft to 42 Degree Gearbox (ARADMAC)</u>

Power is directed from the main transmission to a 42 degree gearbox, then to a 90 degree gearbox, and to the helicopter tail rotor. Information obtained from ARADMAC (Survey Form No. 145) indicates a low usage of 15 percent on both of the mating splines. Reducing the usage below 15 percent may be difficult. The material of both splines is AMS 6260 with the same case and core hardness specified.

3. 90 Degree Tail Shaft (ARADMAC)

The 90 degree shaft receives its power from the 42 degree gearbox. The splines in question (Survey Form No. 142) have a 20 percent usage, operating for 2000-3000 hours, which is quite good for a spline connection operating at a calculated 2560 psi tooth load. ARADMAC engineers propose to utilize corrosion and wear resistant coatings on the mating surfaces in an attempt to extend the life even further.

4. Engine Shaft to Transmission (ARADMAC)

The shaft from the T-55 engine gearbox to the transmission on the CH-47 helicopter is lubricated with a MIL-L-23699 oil (Survey Form No. 136). Similar materials are used for the mating connections, namely, AISI 9310 steel producing usage rates of 10 and 60 percent for the male and female splines, respectively. Survey Form No. 137 reported a similar usage of 5 and 50 percent for the male and female splines, respectively. It was stated that wear is often on the backside of the spline teeth. The splines are lubricated with MIL-L-23699 oil.

The drive shaft assembly on the UH-1 helicopter (Survey Form No. 144) utilized a spline connection on the accessory, Bell P/N 204-040-010-7. This spline connection is lubricated with FSN 9150-926-1969 grease. It is suspected that the major factor relating to a usage of 40 and 80 percent, respectively, for the male and female splines is directly related to the loss of grease at the boot seal. It is recommended that adequate grease retention techniques be utilized.

5. Engine to Gearbox (North Island)

One problem area was reported for an input pinion shaft on a T-64 engine used on an H-53 helicopter. This pinion shaft is located between the engine and the gearbox and rotates at about 13,600 rpm. The spline connection is lubricated with MIL-G-3545 grease. No corrective action was reported for the spline connection.

D. Auxiliary Power Units (AiResearch, Bendix, Navy)

Auxiliary power systems are used on aircraft to supply electrical power for operation of air conditioning, electrical circuits, and some

electric-hydraulic systems. A typical unit is comprised of a turbine and compressor driving a gearbox through a high speed shaft. Splines are usually crowned, unlubricated, and operate in an oil vapor environment. The gearbox, similar to an aircraft engine accessory gearbox has various interface connections for the fuel pump, oil pump, generator, etc. Many designs drive up to about six accessories. Most of the accessories operate at low speed, and no spline problems were reported.

The major problem in the APU's can be related to the high speed operation (40,000 to 60,000 rpm), and to the large overhanging mass at the turbine side of the unit. Due to this mass, a bending action is created in the quill shaft operating through the turbine impeller up to the compressor impeller. The AiResearch design utilized a 7-inch long shaft to connect the compressor-turbine to the high speed pinion. The high speed of the system with the overhanging mass allows the spline connection at the compressor side to describe a path of a circle having a displacement of about 0.010 to 0.012 inches. In order to accept this misalignment, AiResearch crowns that spline connection (Survey Form Nos. 160 and 162). In general, most of the spline connections for the APU's will last up to about 3000 hours and are normally not lubricated; however, the connection is an oil vapor environment.

The Bendix Corporation furnishes units up to about 15 kva with a construction similar to the AiResearch units. For commercial applications, the APU's are usually accompanied by a warranty for 3000, 5000, or increments up to 10,000 hours. No warranties are provided on military units.

Alameda engineers reported (Survey Form No. 212) problems with an AiResearch APU compressor wheel and mating spline shaft. The accessory has a scheduled overhaul at 3000 hours. It was reported that the compressor wheel should have an interference fit with the mating shaft. The O. H. manual (NAVAIR 03-105CA-14) does not specify any spline wear limits. Visual rejection is used. No rejection criteria are specified.

E. Power Plant (Navy, Kelly)

A typical power plant has over 36 spline connections, many of these are fixed and are used to transmit power with essentially no movement between the mating splines. Some splines used within the engine move axially as the temperature of the engine changes.

The major consensus of NAVAIREWORKFAC powerplant personnel is that splines within the engine operate satisfactorily. Many high speed

parts within the engine have mandatory retirement times, therefore, increasing the spline life may not be necessary so long as the splines will operate properly up to the scheduled retirement times specified.

1. Compressor Section (Jacksonville)

One problem is related to a Pratt & Whitney J-52 engine (Survey Form No. 189). This spline connection is located within the engine at the cool "C" section. Normally, the spline in this area will operate properly up to about 2000 hours before it needs replacement or rework. The spline can be reworked in accordance with PPC No. 95 (Appendix E, Item 5b) which specifies that a section of the hub be machined off and a spline-sleeve be used to replace the worn spline. The connection is pinned in eight places. It was estimated that the spline connection operates at 250°F. The spline connection is lubricated with MIL-L-23699 oil.

2. Scavenge Pump (North Island)

Another spline problem is related to a No. 3 scavenge oil pump located within a J-79 engine used on the F-4 aircraft (Survey Form No. 231). This drive consists of a 6-inch long flexible shaft incorporating splines at both ends, one crowned and one uncrowned.

Excessive bending can cause permanent deformation in the flexible shaft. Sometimes uncrowned splines exhibit excessive wear, however, it is difficult for NAVAIREWORKFAC personnel to say which is the exact cause for rejection, excessive wear or excessive bending. The fit between the mating noncrowned splines is relatively tight, which in this case is acceptable since the flexible shaft is incorporated to accept the majority of the apparent misalignment imposed on the spline connection. The highly crowned spline on the other end of the flexible shaft was reported to operate satisfactorily. The spline connection operates at about 300-350°F.

3. Compressor Disk Assembly (Kelly)

Kelly personnel provided information describing that manufacturers recommended improvement programs (Appendix E, Items 11a and 11b) for alievating spline wear in two areas of the TF-39 engine on C-5 aircraft (Survey Form Nos. 234 and 235). These recommendations were made following engine tests and gearbox dynamometer tests in which excessive spline wear was exhibited. One problem area involved the splined adapter for the stage 2 compressor disk assembly. The recommendations involved a less stiff duplex ball bearing, a seal for retaining

oil in the spline mesh, and an enlarged oil nozzle to double oil flow to the spline. The second problem area involved the inlet gearbox horizontal and radial shaft splines. The recommendations (which have been implemented) consist of additional oil jets to positively lubricate the splines and increasing the hardness of the horizontal shaft spline.

F. Shaft Power (Kelly, Quonset Point, North Island)

Shaft power, as the name implies, transmits power from the engine (usually from an angle drive) to the engine accessory gearbox. This design is external to the engine and is used on some engines which do not provide power directly from the engine to the gearbox. The Bendix Corporation is the major supplier of two basic types:

1. Diaphragms and Splines

A hollow Teflon-coated telescoping splined shaft having multiple diaphragms (type of universal joint) is attached to either end of the shaft. A female spline is attached to each of the diaphragm ends. One end mates with a dog-bone spline on the engine and the other mating with another dog-bone spline at the gearbox. In a few instances, this shaft power is used to transmit power to the CSD accessory (Survey Form No. 204). The B-52, F-101, KC-135 and other aircraft utilize the diaphragm-spline design. Only one shaft per engine is required. Six spline problem areas were reported relating to shaft power as noted below:

Aircraft	Engine	Survey Form Nos.	Facility
S2-E1B	R-1820	204	North Island
S2-D, S2-E, S2-E1B	R-1820	187	Quonset Point
T-38	J-85	112, 236, 237, 245	Kelly

2. Diaphragms and Flanges

The other design used eliminates the spline connections completely by incorporating multiple diaphragms with a flanged connection attached to the diaphragms at each end of the shaft. One end of the flange connection bolts onto a mating flange connection at the engine location and a similar one at the gearbox location. Some designs still maintain the telescoping feature for assembly and removal purposes. Bendix proposed to use this design on the F-15, F-14 (Navy), SST, and D-1 aircraft. It was reported that some of these splines will operate up to 16,000 rpm.

G. Gearbox-Accessories

The engine accessory drive gearbox is usually located beneath the engine and is driven either by shaft power or directly from within the engine. The gearbox is normally designed to drive the following accessories: generator or generators, constant-speed drive, starter, fuel pump, fuel control, hydraulic pumps, tachometer, generator, and one or more oil pumps. The two accessories critical for flight are the fuel and hydraulic pumps. The accessories are attached to the gearbox by means of a breech-lock, flange connections, or Marman-type clamps with some means of alignment as specified in the AND and MS standards. In essentially all of the cases studied, none of the female splines on the gearbox can be removed without disassembling the entire gearbox. Consequently, the overhaul time of the gearbox could be controlled by the life of the female interface splines. Since the majority of the spline problems found in this survey are related to the accessory and gearbox, each of the accessories will be discussed.

1. Starter (Air Force, Army, Navy)

There are three types of starters, namely: air (fuel or cartridge actuated), electric, and hydraulic starters. Combination starter-generators are also used. The major starter manufacturers are AiResearch, Bendix, and Hamilton Standards. The starters usually operate for 15 to 45 seconds during which time the engine is started. The speed of operation is usually from 0-8000 rpm. Starters are usually splined into a gearbox and utilize some type of disengaging mechanism to disconnect the starter rotation from the gearbox once the engine has started. Two types are used:

a. Automatic-disengaging gear-type
b. Sprag overrunning clutch

The automatic-disengaging gear-type is illustrated in Figure 4. In this design, the male spline on the starter is bolted directly into the female spline of the gearbox, thereby ensuring that no relative motion is obtained between the male and female splines, thus minimizing or eliminating the possibility of spline wear at the gearbox. Bendix starters utilizing this design are used on the following aircraft:

J-52	J-64	J-75	TF-30
J-55	J-65	J-79	TF-41
J-57	J-73	T-56	

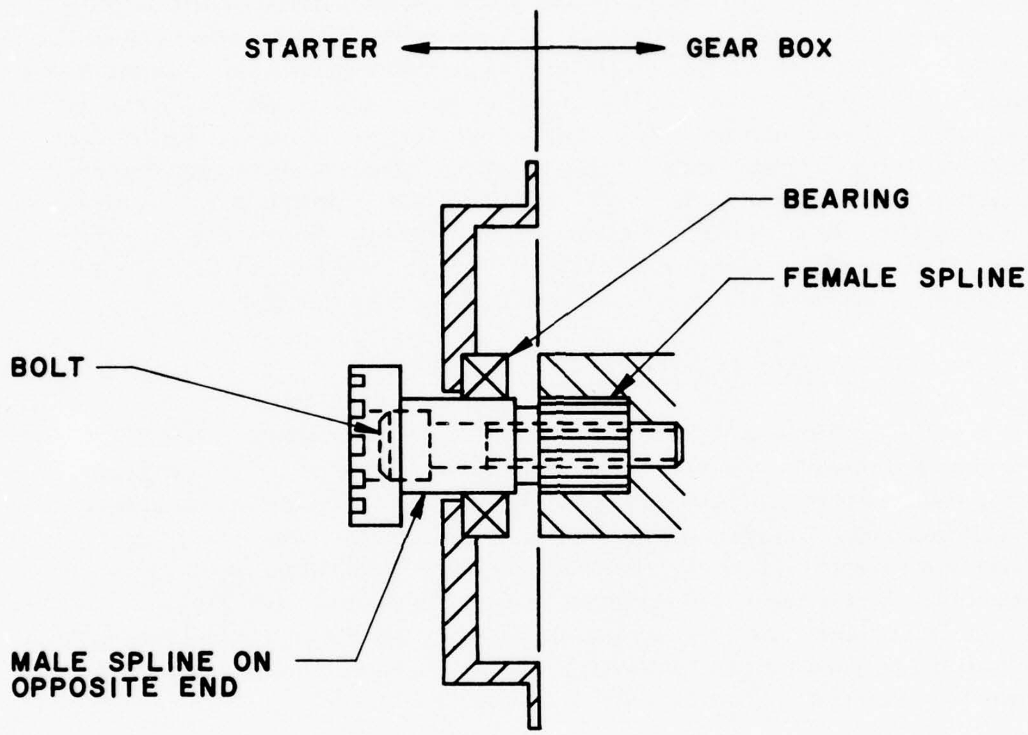

FIGURE 4. AUTOMATIC DISENGAGING GEAR-TYPE STARTER DRIVE

The principal advantage of this design is that after the engine has started, there is complete disengagement from the engine of nearly all of the rotational mass of the starter. Thus, during engine operation, only a very light load is transmitted through the bolt-on splines.

The Sprag overrunning clutch design (conventional male and female spline connection) has a greater rotational mass attached to the spline connection, and is subjected to intermittent and partial engagement of clutch fingers during engine operation. The gear-type design is more expensive than the Sprag design; however, it is considered to be the better of the two designs.

Starters, in general, are designed for the following duty:

	Start Cycles	Engine Hours
Military	1200	1000
Commercial	5000	5000

In most cases, since the start times are very short, the splines do not have the opportunity to wear during that time. Also, in many cases, the engine will drive the splines on the starter (during flight) causing the splines to wear on the opposite sides of the teeth. The debris formation from the wear on the opposite side of the teeth can reduce the effective life of the spline connection.

Ten major starter spline problem areas reported in this survey are listed below:

Aircraft	Engine	Survey Form No.	Facility	Spline Tooth Load, psi
A4-E, A4-F	J-52	173	Jacksonville	NA
F-4	J-79	197	Tinker	NA
F-9	J-48	122	Pensacola	NA
H-2C, H-46	T-58	205, 228	North Island	NA
P-3, P-3A, C-130	T-56	177	Norfolk	NA
		209	Alameda	3950
UH-1B, UH-1C, UH-1D,	T-53	129*	ARADMAC	185
UH-1F, UH-1H		132*	ARADMAC	205
		133*	ARADMAC	115

* Starter-generators

Half of the spline problem areas reported are starters utilized on helicopters.

2. Hydraulic pump (Navy, Air Force)

The hydraulic pump is considered to be a critical item for flight. Two types of hydraulic pumps are used, namely, the electrically driven hydraulic pump and the gearbox driven pump. The electrically driven hydraulic pump is usually remote from the engine and was not reported to have excessive spline wear.

Ten different spline problems were reported relating to hydraulic pumps driven through the gearbox, six of which are related to helicopters. Hydraulic pumps are manufactured by American Brake Shoe, New York Air Brake, and Vickers, with the majority of spline problem areas related to the New York Air Brake hydraulic pumps.

The hydraulic pump usually incorporates a wobble plate design actuating several small pistons which pump the hydraulic fluid. It was reported that this design produces uneven loads on the support bearing and the spline connection due to the varying loads transmitted to the wobble plate from the pistons. The majority of spline connections between the hydraulic pump and the gearbox utilize a "dog-bone" spline. This may be described as a short 2-in shaft having a spline on either end, with one end engaging into the hydraulic pump and the other end into the female gearbox spline. The tabulation below illustrates the hydraulic pump spline problems identified in this survey:

Aircraft	Engine	Survey Form No.	Facility
A-4	J-65	174	Jacksonville
A-5	J-79	172	Jacksonville
H-2	T-58	202, 241, 242	North Island
H-3	T-58	186	Quonset Point
H-53	T-64	193	Tinker
H-53	T-64	240	North Island
S-2	R-1820	123	Pensacola
T-2	J-85	117	Pensacola

From this, it is evident that the majority of problem areas are on the H-2 and H-3 helicopters utilized T-58 engines.

3. Generators-Alternators (Air Force, Airline, Army, Navy)

Each aircraft engine has a generator driven from the engine accessory gearbox. The generator may be either a brush or a brushless

type with a normal TBO of 1000 and 2000 hours, respectively. Starter-generators are also used in some applications. Many brush generators are being converted to the brushless type to eliminate arcing problems at high altitudes.

A total of 16 spline problem areas related to generators used on various engines is listed below:

Aircraft	Engine	Survey Form No.	Facility
B-52	TF-33	96	Kelly
C-123K	R-2800	97	Kelly
CH-46	T-62	223	Cherry Point
DC-8	JT-4	214	United
F-8	J-57	221	Cherry Point
H-2C, H-3	T-58	206, 243	North Island
H-3	T-58	185	Quonset Point
H-46	T-58	220	Cherry Point
P-3A	T-56	176	Jacksonville
T-28	R-1820	124, 127, 128	Pensacola
T-2A	J-34	118	Pensacola
T-33	J-85	99	Kelly
UH-1	T-53	134	ARADMAC

As noted from the above tabulation, the majority of generator spline problems are related to helicopters having a T-53 or T-58 engine.

Lockheed engineers reported that some generator spline wear had been experienced on the 60 kva Bendix generator, Model No. 28B95. This generator reportedly had a poor bearing support design which caused the spline shaft to wobble, thereby causing excessive spline wear. The bearing support was redesigned and the excessive spline wear eliminated.

Engineers also reported that some generators utilize an oil cooling system whereby oil is circulated through the generator to dissipate heat. In the case of the General Electric generator, Model 2CM61 used on the A-6A aircraft, and the Bendix generator, Model 28B187-4A used on the F-4 aircraft, oil is provided to the interface spline connection from within the generator through holes located on the generator male spline shaft. It was reported that a design of this type produces minimal spline wear on the generator interface spline.

4. Constant Speed Drive (Air Force, Navy)

In many generator applications, a CSD is provided between the gearbox and the generator to insure that the generator is driven at a constant speed regardless of engine rpm. This CSD is generally a separate unit with an input and an output spline connection. The input spline has a shear section designed to protect the engine accessory gearbox. The CSD is usually located on the main engine accessory gearbox; however, some engines have this unit located in front on the engine inline with the center line of the engine. In this application, the CSD is driven through a small gearbox.

AiResearch manufactures a combination unit called a constant speed drive starter (CSDS).

The CSD has the capability of disengaging during flight in the event that excessive temperatures are generated within the unit. In order for this to be accomplished, most manufacturers have provided a screw thread on the spline shaft going into the gearbox. A mating female screw thread device is used and rotates with the male spline shaft during normal operation. When the temperature limit is exceeded, a mechanical linkage actuates the mechanism and the male spline is backed into the CSD and out of the engine gearbox. Once the CSD shaft is disconnected in flight, it cannot be reengaged by the pilot.

There are four major companies producing CSD units for various engines, namely: AiResearch, General Electric, Lycoming, and Sundstrand, with Sundstrand providing an estimated 80 percent of the units. It was reported that General Electric is phasing out the conventional type CSD units and manufacturing a solid state device called the variable speed constant frequency unit (VESCF). This unit combines the CSD and the generator into one unit.

The major spline problems associated with dry pad CSD interface spline connections and CSD internal spline problems are listed below:

Aircraft	Engine	Survey Form No.	Facility
A-4	J-52	170 (and Kingsville NAS)	Jacksonville
A-4E, A-4F	J-65	207	Alemeda
B-52	P-3	194, 195	Tinker
C-135	TF-33	194, 195	Tinker
F-4	J-79	196, 198	Tinker
F-4B, F-4J	J-79	182	Quonset Point
F-4	J-79	225	North Island
P-3A, P-3C	T-56	178	Norfolk
S-2D, S-2E	R-1820	188	Quonset Point
S-2E	R-1820	203	North Island

The majority of problem areas centered around the F-4 and S-2 aircraft. No CSD problems were reported relating to helicopters.

a. Inline CSD (Navy)

Some models of the A-4 aircraft engine utilize an inline CSD unit to which the generator is attached. This assembly is cantilevered in front of the J-52 engine. It was reported that vibrations from the CSD unit could be a factor in accelerating spline wear.

Jacksonville reworks three CSD units which will be reviewed. The tabulation below illustrates three CSD units with typical designs used at the interface connection:

Manufacturer	Aircraft	Engine	Usage	Design Type	Scheduled OH, hrs	Estimated OH, hrs
GE	A-4A, A-4B, A-4C	J-65	7	Spline dog clutch	1000	1000
Lycoming	A-4E, A-4F, RA-5C, A-7	J-52 J-65	80	Spline-spline (dogbone)	2000	200
Sundstrand	A-7A	TF-30	0	Muff-snap ring dog clutch	2000	2000

The problem of the Lycoming CSD was first discovered at the Kingsville NAS and then at the Jacksonville NAVAIREWORKFAC. It was reported by the Lycoming representative at the Kingsville NAS that the CSD is removed every 120 hours of operation to examine the splines for excessive wear. In several instances, after the splines at the CSD interface have accumulated excessive wear, the CSD must be forced off the front of the engine for removal by means of a puller. The excessive amount of oxide formation within the spline connection makes it very difficult to separate the mating connection.

After examination of a number of the dogbone type spline connections at Jacksonville and Kingsville on the Lycoming CSD units, it became apparent that different amounts of tooth engagement can be expected for this spline connection. The axial location of the dogbone is normally located by means of a snap ring. If the dogbone is installed improperly (which is possible by virtue of this design), the spline would engage further into the CSD unit. Also, if the bottoming spacer is not placed into the mating female spline connection (in the CSD), the dogbone spline could engage even further into the CSD unit thereby providing less

area of contact in the interface connection introducing higher tooth loads and presumably accelerated wear.

Lycoming has proposed to incorporate a muff design (reference Appendix E, Item 6e) to alleviate the problem. Reports indicated that this design was used prior to the dogbone design.

b. CSD Wet-Pad (Commercial)

Sundstrand engineers pointed out that no major spline problems were reported relating to constant speed drives on current commercial aircraft during a recent airline symposium held October 14-16, 1970, in Rockford, Illinois. Sundstrand feels the major reason for this is that the majority of the splines on commercial aircraft have wet pad spline connections. Other Sundstrand CSD units utilized on a dry pad are lubricated with Sundstrand's grease No. 688272. In addition, it was reported that airlines will not mix any grease used on dry pad configurations as do the military.

North Island engineers report that the wet pad design has reduced the usage from about 35 to 2 percent on one Sunstrand CSD application used on the F-4 aircraft (reference Appendix E, Item 8g).

5. Fuel Pump (Air Force, Navy)

There are four major fuel pump manufacturers, namely: AiResearch, Chandler-Evans, Pesco, and TRW. The fuel pump, like the hydraulic pump, is considered a critical item for flight. In most cases, a two-stage high pressure pump is utilized which is spline driven through the engine accessory gearbox. The fuel pump can encounter spline problems relating to the splines operating in air and in fuel environment. Splines operating within the fuel pump are usually not lubricated with a grease, and must depend upon the lubricity of the fuel and any surface treatments utilized on the splines themselves.

A fuel control is also used as a separate accessory and is usually driven from the engine gearbox. In some cases, the fuel control is attached and driven from the fuel pump. Normally the spline driven fuel control operates at low speed and torque and is not considered a major spline problem area. Only one problem area was reported with a fuel control spline located on APU (Survey Form No. 224).

A total of 16 spline problem areas relating to the fuel pump and the fuel control is listed below:

Aircraft	Engine	Survey Form No.	Facility
A-4, A-6	J-52	171	Jacksonville
A-4, A-6	J-52	213	Alemeda
B-52, KC-135	J-57	199, 200	Tinker
H-2C	T-58	226, 229, 230	North Island
F-4	J-79	232	North Island
F-84F	J-65	91	Kelly
T-38	J-85	233, 238	Kelly
OV-10A	T-76	218, 219, 222	Cherry Point
OV-10A	T-76	161	AiResearch
APU	unk	224	Cherry Point

Approximately half of the problems encountered occur within the fuel pump. Only three of the sixteen problem areas were related to the H-2C helicopters utilizing the T-58 engines and Pesco fuel pumps. Nine of the 16 problems were on Pesco fuel pumps.

6. Oil Pump to Hydraulic Pump (Navy)

In conventional jet engines, a number of oil pumps are used within the gearbox to supply oil to the various bearing locations within the engine proper. Additional scavenge oil pumps located within the engine are used to return the oil to the oil tank on the engine. Some fixed and rotary wing aircraft utilize oil pumps which are attached to the engine accessory gearbox. In some helicopter gearboxes, the hydraulic pump is splined onto the oil pump which in turn is attached to the combining gearbox.

Five major spline problem areas related to oil pumps and connections between the oil pumps and hydraulic pumps are listed below:

Aircraft	Engine	Survey Form No.	Facility
H-3	T-58	244	North Island
H-3	T-58	183, 184	Quonset Point
RB-66	J-71	180, 181	Quonset Point

The majority of problem areas are related to oil pumps utilized on helicopters.

VI. DESIGN PRACTICE

An important group of factors affecting spline wear is that of the design practices. The decisions made at the design stage affect nearly all the subsequent factors such as lubrication and maintenance practices. Also, the cost of rectifying any unfortunate design decisions may be very high once a design has been put into service. On the basis of known or projected operating conditions, design decisions must be made with regard to spline geometry which includes both tooth form and spline size, materials, hardness, surface finish, coatings, extent of misalignment, and selection of lubricating method and lubricant. Some of these design factors are specified in various military and industrial design standards.

A. Design Standards

There are a number of standards related to aircraft splines. For convenience these are divided into three categories as follows:

AND Standards for Accessories and Accessory Mounting Pads. These are older design standards in which lubrication method is not specified.

MS Standards for Accessory Flanges and Accessory Drive Pads. These constitute a very recently adopted set of standards for positive oil-lubricated splines.

Miscellaneous Standards. These are a number of standards for splines or other type drives for special purposes.

1. AND and MS Standards

The AND standards have been in existence since about 1946. For a typical spline connection, two standards are required, one for the accessory flange and one for the engine drive pad. The proper combinations of standards and considerable summarized information from the standards are given in AND 10230 (Reference Chart, Aircraft Engine Accessory Drives). Table 7 contains information relating to the mating engine drive, accessory flange, and other summarized information from individual standards. It is evident that there is a large number of standards required for the variety of spline sizes.

The relevant features of the more recent MS standards for positive oil-lubricated splines (wet pad) on accessories are summarized

TABLE 7. SUMMARY OF AND SPECIFICATIONS RELATING TO ACCESSORY SPLINES*

Engine Drive		Accessory Flange		Accessory Nominal Use Of Engine Drive	Type of Engine For Which Engine Drive is Applicable	Speed, rpm	Torque, lb-in			Pitch Dia., in.	Diametral Pitch	Tooth Load, psi**
Drawing No.	Type No.	Drawing No.	Type No.				T_c	T_o	T_s			
AND 20000	X-A	AND 10260	X	Low Speed Fluid Power Pump	All	3250-3750	100		800	0.600	20/40	710
AND 20000	X-B					3550-3750						
AND 20001	XI-B	AND 10261	XI-B	Fluid Power Pump Propeller Control	Turboprop	3250-3750	250	375	1650			1780
AND 20001	XI-C		XI-C	Fluid Power Pump	All		500	750	2200			
AND 20002	XII-A	AND 10262	XII-A	Generator	Reciprocating	7500-8250				0.800	20/30	2000
AND 20002	XII-B		XII-B				1000	1500	4400	1.200		1070
AND 20002	XII-C		XII-C	Power Take-off			1500	2250	6600			1600
AND 20002	XII-D		XII-A	Generator	Turbojet & Turboprop	6000	500	750	2200	0.800		2000
AND 20002	XII-E		XII-B				1000	1500	4400	1.200		1070
AND 20002	XII-F		XII-C	Power Take-off			1500	2250	6600			1600
AND 20002	XII-J		XII-J	Fluid Power Pump	All	3250-3750	600	900	2700	0.800		2400
AND 20002	XII-K		XII-K				1000	1500	4400			1070
AND 20002	XII-M		XII-M	Generator Power Take-off	Reciprocating	7500-8250	2500	3750	1100	1.200		2670
AND 20002	XII-N			Generator Power Take-off	Turbojet & Turboprop	6000						
AND 20002	XII-S		XII-S	Starter		3300±300						
AND 20002	XII-T		XII-T							1.625	16/32	
AND 20002	XII-W		XII-C	Fluid Power Pump	All	3250-3750	1500	2250	6600	1.200	20/30	1600
AND 20003	XIII-A	AND 10263	XIII-A	Fuel Pump		2000-2500	25		450	0.4583	24/48	470
AND 20003	XIII-B		XIII-B				50		600			950
AND 20006	XVI-A	AND 10266	XVI-A	Generator Power Take-off	Reciprocating	7500-8250	1500	2250	6600	1.200	20/30	1600
AND 20006	XVI-B			Generator Power Take-off	Turbojet & Turboprop	6000						
AND 20006	XVI-C		XVI-C	Generator Power Take-off	Reciprocating	7500-8250	2500	3750	11000			2670
AND 20006	XVI-D			Generator Power Take-off		6000						
AND 20006	XVI-S		XVI-S	Starter	Turbojet & Turboprop	3300±300						
AND 20006	XVI-T		XVI-T									
AND 20007	XVII-A	AND 10267	XVII-A	Generator Power Take-off	Reciprocating	7500-8250	4200	6300	18500	1.625	16/32	3290
AND 20007	XVII-B			Generator Power Take-off	Turbojet & Turboprop	6000						
AND 20007	XVII-C		XVII-C	Generator Power Take-off	Reciprocating	7500-8250						
AND 20007	XVII-D			Generator Power Take-off								
AND 20007	XVII-E			Generator Power Take-off	Turbojet & Turboprop	6000						
AND 20007	XVII-F			Generator								
AND 20010	XX-A	AND 10270	XX	Propeller Governor	Turboprop & Reciprocating	2400-2700	125	188	825	0.600	20/40	

*Notes apply to all AND Specifications listed: Hardness, R_c Male Spline 55 max. (Case Depth - Not Specified); Hardness, R_c Female Spline 58 min. (Case Depth - 0.010-in. min.); Surface Texture - No requirement on male or female.

**SwRI Calculated Spline Tooth Load Based on Projected Area.

in Table 8, which contains information taken from MS 3336 (Accessory Drives, Aircraft Engine, Reference Chart for), and MS 3335 (Spline Details-Drive Pads and Accessory Flanges, Design Standard for), and from the individual standards. The majority of the MS standards for the engine accessory gearbox were adopted in June of 1968 while the MS standards for the mating accessory flanges and splines were incorporated in March and November of 1969.

The two sets of standards differ in a number of ways which will be discussed in the following paragraphs.

a. Tooth Geometry

Tooth geometry is not the same for all pitch diameters which are common to both sets of standards, as shown below:

AND Standards			MS Standards		
Pitch dia, in.	No. of teeth	Diametral Pitch	Pitch dia, in.	No. of teeth	Diametral Pitch
0.4583	11	24/48	0.4583	11	24/28
0.6000	12	20/40	0.6000	12	20/40
0.800	16	20/30	0.8000	16	20/40
1.200	24	20/30	1.200	24	20/40
1.625	26	16/32	1.6250	26	16/32
			2.000	32	16/32

The major difference in tooth geometry is in the diametral pitch/stub pitch ratio. The MS standards call for a 1/2 ratio for all pitch diameters, whereas in the AND standards, both 1/2 and 2/3 ratios were used. As the above table shows, there are only three pitch diameters common to both sets of standards that have the same diametral pitch to stub pitch ratio. Splines of the other two pitch diameters are not interchangeable between design standards.

b. Hardness

The two sets of standards also differ in hardness and case depth requirements. The AND standards specify that the hardness of the male spline will be 55 R_c or less, and that the female spline will be 58 R_c or greater. The case depth on the male spline is not specified and on the female a minimum case depth of 0.010-in. is specified. The MS standards call for 56 R_c minimum for both splines with no case depth requirement.

TABLE 8. SUMMARY OF MS SPECIFICATIONS RELATING TO ACCESSORY SPLINES*

Engine Drive Pad	Dash No.	Accessory Flange	Drive Ratings: Nominal Speed rpm	Drive Ratings: Rated Torque lb. in. **	Drive Ratings: Rated Power HP	Tooth Load psi***	MS3335 Spline Pitch Dia. in.	Diametral Pitch
MS3325	-1	MS3330	16,000	150	-	3,180	0.4583	24/48
	-2		4,200	15	-	320	0.4583	
MS3326	-1	MS3331	12,000	(30)	6	290	0.600	20/40
	-2		12,000	(60)	12	580	0.600	
	-3		8,000	600	-	2,650	0.800	
	-4		16,000	300	-	2,900	0.600	
	-5S		3,300	750	-	7,260	0.600	
	-6S		3,300	1,500	-	14,520	0.600	
MS3327	-1	MS3332	8,000	(236)	30	1,040	0.800	
	-2		12,000	(158)	30	700	0.800	
	-3		8,000	500	-	2,210	0.800	
	-4		4,000	1,000	-	1,460	1.200	
	-5		6,000	1,500	-	2,180	1.200	
	-6		4,000	1,500	-	2,180	1.200	
	-7S		3,300	1,800	-	7,960	0.800	
	-8S		3,300	4,800	-	6,990	1.200	
	-9S		3,300	7,200	-	10,480	1.200	
MS3328	-1	MS3333	8,000	(236)	30	1,040	0.800	
	-2		12,000	(158)	30	700	0.800	
	-3		8,000	(315)	40	460	1.200	
	-4		8,000	(512)	65	740	1.200	
	-5		8,000	(236)	30	1,040	0.800	
	-6		12,000	(158)	30	700	0.800	
	-7		8,000	(355)	45	1,570	0.800	
	-8		4,000	4,000	-	2,580	1.625	16/32
	-9		6,000	4,000	-	2,580	1.625	
	-10S		3,300	7,200	-	10,480	1.200	20/40
	-11S		3,300	14,400	-	9,270	1.625	16/32
MS3329	-1	MS3334	8,000	(472)	60	690	1.200	20/40
	-2		8,000	(630)	80	920	1.200	
	-3		8,000	(940)	120	600	1.625	16/32
	-4		8,000	(1,420)	180	910	1.625	
	-5		8,000	(1,890)	240	1,220	1.625	
	-6		6,000	(472)	45	2,090	0.800	20/40
	-7		6,000	(682)	65	3,010	0.800	
	-8		6,000	(1,000)	95	1,460	1.200	
	-9		6,000	(1,470)	140	2,140	1.200	
	-10		6,000	(2,100)	200	3,060	1.200	
	-11		4,000	4,000	-	2,580	1.625	16/32
	-12		4,000	9,000	-	3,160	2.000	

*Notes apply to all MS Specifications Listed: Hardness, R_C: Male and Female Splines 56 min. (Case Depth - Not Specified, Surface Texture 63 μin.).
**SwRI Calculated Values (in parentheses).
***SwRI Calculated Spline Tooth Load Based on Projected Area.

c. Surface Finish

There is no surface texture requirement in the AND standards. The MS standards call for a surface texture of 63 microinches on spline tooth surfaces.

d. Tooth Loads

Higher calculated tooth loads are allowed for the MS splines than for the AND splines as shown below:

Pitch dia, in.	Range of Rated Tooth Loads, *psi AND Stds.	MS Stds.
0.4583	470 - 950	320 - 3180
0.6000	710 - 1780	290 - 14,520
1.625	3290	600 - 9270

e. Lubrication

The two sets of standards also differ somewhat with respect to lubrication specifications. The AND standards do not specify a lubrication method for the splines. In fact, only AND 20007 states that "Provision for spline lubrication shall be provided. If the form is fluid, accessible provision shall be made to prevent flow in the event flow is not desired." It should be noted that all of the AND standards listed in Table 7 (except for 10270 and perhaps 20010 which was not available) specify that the accessory should operate with a leakage of not more than 2cc per hour of oil from the engine into the pilot compartment. Several of these standards also provide for positive oil flow to the accessory, but in each case, the splines are sealed off from this oil by a gasket. The MS standards listed in Table 8 all specify that "positive engine oil lubrication shall be provided to the spline."

f. Spline Misalignment

The manner in which spline misalignments are specified differ somewhat between the two sets of standards. Both AND and MS standards specify the concentricity (lateral misalignment) between the engine or drive mounting pad pilot and the spline axis and angular misalignment between spline axis and mounting pad face. In the case of the accessory, both sets of standards specify the lateral but not the angular misalignment between mounting flange pilot and the axis of rotation. In addition, each set of standards has lateral and angular

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* Calculated load on projected area.

misalignment specifications pertaining to the spline in the assembled accessory. In the AND standards it is stated that the accessory must operate with specified lateral and angular misalignments of the drive spline; these misalignments are in most cases equal to or slightly greater than the misalignments allowed for the spline in the engine pad. Thus, in the AND standards angular misalignment of the accessory spline is not directly specified but is only inferred. In the MS standards it is specified that the axis of the radially-loose spline or coupling shall not be laterally or angularly misaligned more than specified amounts with respect to the axis of the pilot diameter on the accessory flange.

The maximum combined allowable misalignments resulting from drive-pad and accessory-flange misalignments are given in Tables 9 and 10 for the AND and MS standards, respectively. The maximum combined allowable lateral misalignment was taken as one-half the sum of engine pad and accessory misalignments and maximum pad clearance. The newer MS standards allow slightly greater combined lateral misalignment (0.0085 to 0.0090 in.) than do the AND standards (0.0075 to 0.0085 in.). The significance of these lateral misalignments is perhaps best understood in conjunction with the allowable chordal clearances. In a spline connection, if the combined lateral misalignment of the mating splines exceeds the combined chordal clearance interference will result. Both sets of standards allow maximum combined lateral misalignments in excess of the minimum chordal clearances; hence interference in the spline teeth would be expected in some cases.

The standards appear to be deficient in several respects. The AND standards lack surface texture requirements and clearly defined angular misalignment requirements for splines on the accessory. One standard, AND 10266, does not specify the allowable lateral misalignment of the spline on the accessory.

The MS standards appear to be more uniform and consistent than the AND specifications, although they are lacking a case depth requirement.

2. Miscellaneous AND and MS and Industrial Standards

In addition to the AND and MS standards for accessories and accessory drive pads which are applicable to splines, there are several other standards for either different types of drives or for splines for special applications. These standards are listed for reference in Table 11.

TABLE 9. SPLINE MISALIGNMENT AS SPECIFIED BY AND STANDARDS 10260-10270 AND 20000-20010

Splines		Engine and/or Gearbox			Accessory			Engine and/or Gearbox and Splines with Accessory						
Male and Female			Engine Accessory Misalignment			Accessory Mounting Misalignment		Accessory Must Operate with Specified Misalignment of Drive Spline		Combined Chordal Clearance, in.		Maximum Pilot Clearance	Maximum Combined Misalignment	
Pitch Dia. in.	Diametral Pitch	Engine Drive	Lateral, in. (TIR)	Angular, in. (TIR)	Accessory Flange	Lateral, in. (TIR)	Angular	Lateral, in.	Angular, in. (TIR)	Min	Max.	in.	Lateral, (Calculated) in.	Angular, (Calculated)
0.600	20/10	AND 20000	0.006	0.004	AND 10260	0.004	Not stated	0.006	0.005	0.0051	0.0074	0.005	0.0075	0.004
0.600	20/40	AND 20001	0.006	0.004	AND 10261	0.004	"	0.006	0.005	0.0051	0.0074	0.007	0.0085	0.004
0.800	20/30	AND 20002	0.006	0.004	AND 10262	0.004	"	0.006	0.005	0.0056	0.0079	0.007	0.0085	0.004
1.200	20/30	AND 20002	0.006	0.004	AND 10262	0.004	"	0.006	0.005	0.0056	0.0079	0.007	0.0085	0.004
1.625	16/32	AND 20002	0.006	0.004	AND 10262	0.004	"	0.006	0.005	0.0056	0.0079	0.007	0.0085	0.004
0.458	24/48	AND 20003	0.006	0.006	AND 10263	0.004	"	0.006	0.005	0.0042	0.0092	0.006	-	0.006
*	*	AND 20004	-	-	AND 10264	-	-	-	-	-	-	-	-	-
**	**	AND 20005	-	-	AND 10265	-	-	-	-	-	-	-	-	-
1.200	20/30	AND 20006	0.006	0.008	AND 10266	Not stated	"	0.009	0.009	0.0059	0.0109	0.011	-	0.008
1.625	16/32	AND 20006	0.006	0.008	AND 10266	"	"	0.009	0.009	0.0061	0.0093	0.011	-	0.008
1.625	16/32	AND 20007	0.006	0.004	AND 10267	0.004	"	0.006	0.005	0.0061	0.0111	0.007	0.0085	0.004
1.625	16/32	AND 20007	0.006	0.004	AND 10267	0.004	"	0.006	0.009	0.0061	0.0111	0.007	0.0085	0.004
***	***	AND 20008	-	-	AND 10268	-	-	-	-	-	-	-	-	-
*	*	AND 20009	-	-	AND 10269	-	-	-	-	-	-	-	-	-
0.600	20/40	AND 20010	0.006	0.004	AND 10270	Spec. not available		-	-	-	-	-	-	-

*Ramp-type teeth, not pertinent to the survey.
**Square drive, not pertinent to the survey.
***4-tang coupling, not pertinent to the survey.

TABLE 10. SPLINE MISALIGNMENT AS SPECIFIED BY MS STANDARDS

Splines		Engine and/or Gearbox				Accessory					Engine and/or Gearbox and Splines with Accessories				
Male and Female		Drive Pad		Drive Pad, Spline-to-Pilot Misalignment			Accessory Flange, Axis of Rotation-to-Pilot Misalignment		Accessory Flange, Spline-to-Pilot Misalignment		Combined Chordal Clearance, in.		Maximum Pilot Clearance	Maximum Combined Misalignment	
Pitch Dia. in.	Diametral Pitch	MS No.	Dash No.	Lateral, in. (TIR)*	Angular, in./in. (TIR)*	Accessory MS No.	Lateral, in. (TIR)*	Angular, in./in. (TIR)*	Lateral, in.	Angular, in./in.	Min.	Max.	in.	Lateral, in. **	Angular, in./in. ***
0.4583	24/48	3325	-1, -2	0.006	0.001	3330	0.006	Not Stated	0.006	0.003	0.0050	0.0098	0.005	0.0085	0.004
0.600	20/40	3326	-1, -2 -4, -5S, -6S	0.006	0.001	3331	0.006	"	0.006	0.003	0.0054	0.0106	0.006	0.0090	0.004
0.800	20/40	3326	-3	0.006	0.001	3331	0.006	"	0.006	0.003	0.0058	0.0112	0.006	0.0090	0.004
0.800	20/40	3327	-1, -2, -3, -7S	0.006	0.001	3332	0.006	"	0.006	0.003	0.0058	0.0112	0.006	0.0090	0.004
1.200	20/40	3327	-4, -5, -6 -8S, -9S	0.006	0.001	3332	0.006	"	0.006	0.003	0.0066	0.0124	0.006	0.0090	0.004
0.800	20/40	3328	-1, -2, -5, -6, -7	0.006	0.001	3333	0.006	"	0.006	0.003	0.0058	0.0112	0.006	0.0090	0.004
1.200	20/40	3328	-3, -4, -10S	0.006	0.001	3333	0.006	"	0.006	0.003	0.0066	0.0124	0.006	0.0090	0.004
1.625	16/32	3328	-8, -9, -11S	0.006	0.001	3333	0.006	"	0.006	0.003	0.0074	0.0132	0.006	0.0090	0.004
1.200	20/40	3329	-1, -2, -8, -9, -10	0.006	0.001	3334	0.006	"	0.006	0.003	0.0066	0.0124	0.006	0.0090	0.004
1.625	16/32	3329	-3, -4, -5, -11	0.006	0.001	3334	0.006	"	0.006	0.003	0.0074	0.0132	0.006	0.0090	0.004
0.800	20/40	3329	-6, -7	0.006	0.001	3334	0.006	"	0.006	0.003	0.0058	0.0112	0.006	0.0090	0.004
2.000	16/32	3329	-12	0.006	0.001	3334	0.006	"	0.006	0.003	0.0081	0.0141	0.006	0.0090	0.004

*Total Indicator Reading.
**One-Half (Drive Pad, Spline-to-Pilot + Accessory Flange Axis of Rotation-to-Pilot Misalignment + Maximum Pilot Clearance).
***Drive Pad, Spline-to-Pilot + Accessory Flange, Spline-to-Pilot Angular Misalignments.

TABLE 11. MISCELLANEOUS AND AND MS STANDARDS RELATED TO AIRCRAFT SPLINES, SERRATIONS, AND OTHER DRIVES

Standard No.	Title	Remarks
AND 10237	Spline, serration	Gives geometry of nominal 0.250-in. O.D., 36 tooth, straight sided serration with 3 serrations omitted for indexing.
AND 10264	Flange-Type XIV Accessory Mounting	Ramp-type drive
AND 10265	Flange-Type XV Accessory Mounting	Square drive
AND 10268	Flange-Type XVIII Accessory Power Input	Flange-type drive
AND 10269	Flange-Type XIX Accessory Mounting	Ramp-type drive
AND 20004	Drive-Type XIV Engine Accessory	Ramp-type drive
AND 20005	Drive-Type XV Engine Accessory	Square drive
AND 20008	Drive-Type XVIII Engine Accessory	Flange-type drive
AND 20009	Drive-Type XIX Engine Accessory	Ramp-type drive
MS 18054	Drive Pads for Aircraft Electric Equipment, Circular, 5-, 8-, and 10-inch	This standard supersedes AND 20002 and 20006 for BuWEP use with electrical equipment
MS 33568	Drive, Square Mounting Flange with Involute Spline Pinion	Describes flange details and tooth geometry for splines which serve as pinion gears
MS 33569	Drive, Round Mounting Flange with Involute Spline-Pinion	Describes flange details and tooth geometry for splines which serve as pinion gears

There also exist a sizable number of industrial standards applicable to aircraft splines, as shown in Table 12.

B. Materials

According to the information obtained from the spline drawings collected during the survey, the vast majority of splines were made of steel alloys, as shown in Table 13. Fifty-eight out of 61 male splines were steel alloys (seven of these are of unknown composition). Fifty-five out of 62 female splines were steel alloys (three of these of unknown composition). The most frequently used spline material was AMS 6260 (or AISI 9310); this alloy was specified for 12 male and 33 female splines. The next most frequently used material was AMS 6415 (or AISI 4340) which was specified for 15 male and four female splines. The AMS 6260 is a low carbon alloy steel of moderate hardenability and must be carburized if surface hardness in excess of R_c 44 is desired. When carburized and properly heat treated the alloy can provide a hard case and a much softer more ductile core; this combination of desirable properties probably accounts for the popularity of AMS 6260 as a spline material, particularly for female splines. The AMS 6415 alloy is a medium carbon alloy steel with good hardenability. It would appear to be a good choice for a male spline material since with proper tempering after quenching, it would exhibit hardness below R_c 55. It is not well suited for female splines that must conform to a requirement of R_c 58 minimum surface hardness since R_c 58 is approximately the upper limit of hardness possible with this alloy unless it is carburized.

Only a small number of non-ferrous splines were encountered: one male and three female splines of titanium alloys, one male and one female spline of copper-beryllium alloys, and one female spline of aluminum bronze.

C. Geometry

All available information on geometry of the problem splines is compiled in Table 14. The vast majority (75 out of 83 splines) of the survey splines had straight involute teeth. Six cases of crowned involute teeth were encountered, one case of a helical involute spline, and one case of a spline with straight-sided teeth.

Among the splines with involute tooth form slightly over half (42) had a diametral pitch to stub pitch ratio of 1/2; 35 splines had a ratio of 2/3; one helical spline had a 3/7 ratio; and four splines had a 1/1 ratio

TABLE 12. INDUSTRIAL STANDARDS FOR AIRCRAFT SPLINES (SAE Unless Otherwise Indicated)

Standard No.	Title
AS 44	Starter, Mounting Pads and Drives, Types I, II, III, and IV
AS 46	Generator, Mounting Pad and Drive, 4 Bolt
AS 47A	Pump, Fuel, Mounting Pad and Drive
AS 54	Tachometer Drive - Type I
AS 55A	Tachometer, Mounting Pad and Drive - Type II
AS 84B	Splines, Involute (Full Fillet)
AS 468B	Drive-Accessory, 5'' Bolt Circle
AS 469B	Drive-Accessory, 8'' Bolt Circle
AS 470B	Drive-Accessory, 10'' Bolt Circle
AS 471B	Flange-Accessory, 5'' Bolt Circle
AS 472B	Flange-Accessory, 8'' Bolt Circle
AS 473B	Flange-Accessory, 10'' Bolt Circle
AS 518	Drive Accessory 3.000 Pilot Diameter-QAD
AS 519	Drive Accessory 4.125 Pilot Diameter-QAD
AS 520	Drive Accessory 6.500 Pilot Diameter-QAD
AS 521	Drive Accessory 9.000 Pilot Diameter-QAD
AS 522	Flange Accessory 3.000 Pilot Diameter-QAD
AS 523	Flange Accessory 4.125 Pilot Diameter-QAD
AS 524	Flange Accessory 6.500 Pilot Diameter-QAD
AS 525	Flange Accessory 9.000 Pilot Diameter-QAD
AS 532	Drive - 3/4 Generator - 8'' BC Male Pilot
AS 533	Flange-3/4 Generator - 8'' BC Female Pilot
AS 534	Drive-3/4 Generator -10''BC Male Pilot
AS 535	Drive-3/4 Generator - 10'' BC Female Pilot
AS 959	Drive-Studded, Accessory, 2.653 BC Square, Design Standard for
AS 960	Flange Accessory, 2.653 BC Square, Design Standard for
AS 961	Drive-Studded, Accessory, 5.000 BC Square, Design Standard for
AS 962	Flange Accessory, 5.000 BC Square, Design Standard for
AS 963	Drive-Studded, Accessory, 5.000 BC Round, Design Standard for
AS 964	Flange Accessory, 5.000 BC Round, Design Standard for
AS 965	Drive-Studded, Accessory, 8.000 BC Round, Design Standard for
AS 966	Flange Accessory, 8.000 BC Round, Design Standard for
AS 967	Drive-Studded, Accessory, 10.000 BC Round, Design Standard for
AS 968	Flange Accessory, 10.000 BC Round, Design Standard for
AS 969	Drive-Accessory 5.000 BC Round, QAD, Design Standard for
AS 970	Drive-Accessory, 8.000 BC Round, QAD, Design Standard for
AS 971	Drive-Accessory 10.000 BC Round, QAD, Design Standard for
AS 972A	Spline Details, Accessory Drives and Flanges
ARP179A	Involute Spline Gages (30° Pressure Angle)
ARP365	Drives - Square Flange. 0.600 PD Spline Accessory
B92.1 1970 (ANSI)	Involute Splines & Inspection (Provide guidance & data for design of straight (nonhelical splines)
R14 1955 (ISO)	Straight-Sided Splines (for Cylindrical Shafts), Nominal Dimensions in Millimeters (Involute Spline Teeth)

TABLE 13. MATERIALS USED IN PROBLEM SPLINES

Specified Material	Male Splines Navy	Male Splines Others	Female Splines Navy	Female Splines Others
AMS 6260 or AISI 9310	5	7	23	10
AMS 6415 or AISI 4340	5	10	1	3
AISI E-4350-1	1	4	0	0
AISI 3310	4	0	0	0
AISI 4140	0	2	0	2
AISI 4620	0	1	0	2
AMS 6470 or Nitralloy 135 mod.	2	0	1	1
AISI M 50	1	1	1	0
AMS 6475 or Nitralloy N	0	2	1	0
AMS 2485	2	0	0	0
AMS 6471	0	0	2	0
AMS 5648 or AISI 316	1	0	0	0
AMS 6265	0	0	1	0
AMS 62630	0	0	1	0
AISI H-11	1	0	0	0
AISI 6150	1	0	0	0
AISI M-2	0	0	1	0
AISI H-2 HS	0	0	1	0
AISI 52100	0	0	0	1
AISI 4640	0	0	0	1
*Nitriding Steel	1	0	0	0
*B50TA-317B1	2	0	0	0
*PM 6003	1	0	0	0
*QQ 570	2	0	0	0
*PDS10306CG	1	0	0	0
*QQ-T-590	0	0	1	1
*C50TF/6	0	0	0	1
**Titanium AMS 4928	2	0	0	0
**Titanium	0	0	1	1
**Titanium BG 42	0	0	1	1
**Copper-Beryllium	1	0	1	0
**Aluminum Bronze	0	0	0	1
*PM 6007	1	0	0	0
Total	34	27	37	25

*Steel of uncertain material.
**Non-ferrous Metals.

TABLE 14. GEOMETRY OF PROBLEM SPLINES

Tooth Form	No. of Splines Navy	No. of Splines Others
Straight Involute	48	27
Crowned Involute	3	3
Helical, Involute	1	0
Straight, straight-side	1	0
Total	53	30
Diametral Pitch/Stub Pitch		
1/2	26	16
2/3	24	11
3/7	1	0
1/1	1	3
Total	52	30
Type of Fit		
Side Fit	14	14
Major Diameter Fit	1	1
Total	15	15

indicating that they had full depth teeth identical to a gear of the same diametral pitch.

The type of fit is frequently not specified on the spline drawings, but in 28 out of 30 cases where it was specified a side fit was specified and in two cases a major diameter fit called for.

D. Surface Finish

Surface finish tolerances were not shown on many of the spline drawings obtained. The frequency with which various surface finishes were specified is shown in Table 15.

E. Coatings

Based on the available information, coatings of one sort or another were applied to 20 of the male and 18 of the female survey splines, as shown in Table 16. Chromium flash coatings (less than 0.001-in. thick) were specified in eleven instances and copper flash coatings were called for in six instances.

F. Comments on Design Standards

This discussion will be confined to the AND and MS standards since they are used mostly for aircraft splines. As shown earlier, the newer MS standards cover a somewhat wider spline size range than the older AND standards. Perhaps the newer standards are intended to replace the older standards. If so, this should be indicated on the MS standards, and the AND standards should be withdrawn.

In the newer MS standards, grooves shown in the drive pad pilot bore and on the accessory flange pilot diameter appear to be for sealing purposes, although this is not so stated. The purpose of these grooves should be stated.

Table 17 summarizes other specific comments on the AND and MS standards. With reference to tooth geometry, both standards specify the involute form, which is of course commonly employed and is believed to be preferable. Both standards define pitch diameter, number of teeth, diametral pitch, etc., covering a range probably quite adequate for accessory drives. The more conservative diametral pitch/stub pitch ratio of 1/2, as specified in the MS standards, is judged to be more preferable. Neither standard provides tooth crowning. However, for applications where relatively large misalignment must be accepted, the use of crowning may have merit (Appendix A).

TABLE 15. SURFACE FINISH SPECIFIED ON PROBLEM SPLINES

Surface Finish in.	Male Splines		Female Splines	
	Navy	Others	Navy	Others
32	3	2	1	2
60	0	1	0	1
63	4	4	5	8
64	0	1	-	-
80	-	-	1	0
90	-	-	2	0
100	1	0	5	0
125	2	2	5	0
130	-	-	1	0
150	2	0	1	0
Total	12	10	21	11

TABLE 16. COATINGS SPECIFIED ON PROBLEM SPLINES

Coating	Male Splines		Female Splines	
	Navy	Others	Navy	Others
Chromium flash	2	2	5	2
Copper flash	2	3	1	-
MIL-L-8937 Dry Film Lubricant	1	-	1	1
Silver flash	-	-	0	2
Electrofilm	0	2	-	-
Nickel + Cobalt	-	-	1	1
Tin + Cadmium	-	-	2	0
Cadmium	2	-	-	-
MIL-L-46010 Dry Film Lubricant	0	1	-	-
QQ-P-416	1	-	-	-
AMS 2410	1	-	-	-
AMS 2485 (Black Oxide)	-	-	1	0
MIL-L-25681B Dry Film Lubricant	1	-	1	0
Microseal 100-1	1	1	-	-
Total	11	9	12	6

Brand names are cited as reported. They do not imply endorsement or otherwise by the authors.

TABLE 17. ADEQUACY OF DESIGN STANDARDS AND CONFORMANCE OF CURRENT PRACTICE TO AND STANDARDS

	AND	MS	Comment on Standards	Percent AND Conformance: Navy	Percent AND Conformance: Others
Geometry	Yes	Yes	Requires study	78	82
Operating Variables	Yes	Yes	Requires study	67	63
Material	No	No	Inadequate	--	--
Surface Finish	No	Yes	Requires study	--	--
Case Thickness	Yes	No	Inadequate	88	100
Case Hardness: Male:	≤55	≥56	Requires study	50	50
Female:	≥58	≥56		86	60
Core Hardness	No	No	Inadequate	--	--
Coating	No	No	Inadequate	--	--
Lubrication Method	No	Wet Pad	Inadequate	--	--
Misalignment	Yes	Yes	Inadequate	--	--

Both standards provide information relating to such operating variables as speed, torque, and tooth engagement. Broadly speaking, the newer MS standards provide for a wider speed range (3,300-16,000 rpm) than the AND standards (2,400-8,250 rpm). Logically, the specified torque is lower in the MS standards (15-14,400 in.-lb) than in the AND standards (100-18,500 in.-lb). On account of the latter, the tooth engagement is slightly increased in the MS standards (0.48-1.485 in. minimum) from the AND standards (0.53-1.18 in. minimum). As explained previously, spline wear is highly dependent on the tooth loading or contact pressure, rather than the torque as such. It was shown in Tables 7 and 8 that the calculated tooth loading for the MS standards (up to 14,520 psi) is considerably higher than for the AND standards (up to 3,290 psi). Since many current interface splines (probably designed to AND standards) are already experiencing troubles, it is apparent that the newer MS standards are inadequate. In any case, the entire problem of tooth loading deserves further study.

Neither the AND nor the MS standards specify a material for use in the male or female splines. As noted from Table 13, a large variety of materials are used for the male and female splines with AMS 6260 and AMS 6415 being the ones most commonly used. Further, Appendix A shows that materials such as M50 may merit consideration. Since material selection can have an effect on spline life, consideration should be given to specifying materials in the design standards.

The AND standards do not specify surface finish. The MS standards call for a surface finish of 63 microinches, which is probably quite acceptable in most cases. However, results presented in Appendix A suggest that a rougher surface may be beneficial in providing a greater grease holding capacity and in facilitating grease flow. Thus, the problem also merits further study.

The case thickness of the male and female splines is not specified in the MS standards, while the AND standards specify 0.010 in. minimum for the female spline only. The case hardness is specified in the AND standards as 55 R_C maximum for the male splines and 58 R_C minimum for the female splines, while the MS standards call for a minimum case hardness of 56 R_C for both the male and female splines. In practice, it is more difficult and costly to replace the female splines, which are usually attached to some major component and thus not easily accessible. The older AND standards appear to accept this fact by making the male splines softer so that they take most of the wear. In this respect, it is believed the newer MS standards represent a backward step. Finally, core hardness has relevance particularly to fatigue, and a requirement in the stardards appears desirable.

As shown in Appendix A, some plastic and particularly metallic coatings can be very effective in mitigating spline wear. Consideration should be given to including them in the design standards.

The MS standards were presumably developed to be used for the wet pad spline connection, while the AND standards are for the dry pad design. However, the AND standards do not make mention that the splines are to be lubricated, consequently the component designer may not take lubrication into the design of the spline connection.

Both the AND and MS standards specify the angular and lateral misalignment for the spline connections. The standards differ in the manner in which misalignment is prescribed for the male splines on the assembled accessory. It would seem desirable for the standards to employ the same method of prescribing the misalignment. The method employed in the MS standards is more direct and understandable and should perhaps replace that used in the AND standards. The terminology of the AND standards is ambiguous and does not definitely specify an allowable misalignment of the male spline on the assembled accessory.

Furthermore, as explained previously, the allowable misalignment in both sets of standards is in excess of the minimum chordal clearance; thus mechanical interference may occur in many of the spline connections. This situation should be studied to determine if clearances and misalignments could be altered to assure no interference between the spline teeth.

G. Conformance of Surveyed Splines to AND Standards

It has been shown that both the AND and the MS standards are inadequate or require careful further study in many respects. Nevertheless, regardless of their inadequacy, it is of interest to examine to what extent the surveyed splines conform to the AND standards. The AND standards are selected for comparison because the majority of the spline wear problems involved splines designed prior to the adoption of the MS standards, thus a comparison against the MS standards does not seem warranted at this time. Further, since the AND standards are for engine accessory drives, comparison between the standards and splines will be confined only to splines on accessories. The results of this comparison are presented in the last two columns of Table 17.

With regard to spline geometry, based on information obtained from the manufacturers' drawings relating to the pitch diameter and the

diametral pitch, it is noted that 78 and 82 percent of the surveyed splines conformed to the AND standards for the Navy and others, respectively.

The AND standards provide information relating to the following operating variables: speed, torque, and tooth engagement. Since the spline tooth load is of extreme importance in spline operation, it was calculated based on the projected area for each of the AND specifications (as noted in Table 7). Similar calculations were performed for the specific spline problem areas and were compared. The results are listed under operating variables in Table 17 and illustrate a 67 and 63 percent conformance by the Navy and others, respectively.

In 17 cases, the tooth loads of surveyed splines were below that corresponding to the AND standards. In nine cases, the tooth loads were excessive. In three cases, the tooth loads were far in excess of those associated with the AND standards, as shown below:

Survey Form No.	Facility	Spline Tooth Load, psi	AND Standards Tooth Load, psi
183	Navy	14,600	710
186	Navy	13,200	710
195	Air Force	13,700	2670

In contrast, some splines had calculated tooth loads far below those associated with AND standards, as shown below:

Survey Form No.	Facility	Spline Tooth Load, psi	AND Standards Tooth Load, psi
133	ARADMAC	115	2000
170	Navy	145	2670
178	Navy	360	2670

The very low design loads cited above are, of course, on the safe side. It is the very wide discrepancies, both too high and too low, that is surprising.

The AND standards specify a case thickness of 0.010 in. minimum for the female spline only. Based on information for the female interface splines, 88 and 100 percent conformed to the standards by the Navy and others, respectively.

The case hardness for the male and female splines is specified in both the AND and MS standards. As noted in Table 17, the conformance with the AND specifications for the male splines rated 50 percent for both the Navy and others. In general, the component manufacturers are making the splines harder than what is specified, presumably to extend the life of their splined parts. The female splines were not as bad for the Navy with a conformance of 86 percent, while the others had a 60 percent conformance.

VII. LUBRICATION PRACTICE

A. Lubricants

Military specifications, such as T. O. s and NAVAIRs, specify the type of lubricant to be used for the majority of spline connections. These lubricants may be divided into three categories, namely: greases, liquids (oils and fuels), and solids.

Table 18 illustrates the lubricants specified by the Navy and others for the spline problem areas encountered in this survey. It is evident that a variety of lubricants are being used for spline connections by both the Navy and by others. The lubricants used are usually specified by military specification, Federal Stock Number, or in some cases by specific brands. Note that brand names are cited as reported. They do not imply endorsement or otherwise by the authors.

1. Greases

Greases comprise the greatest variety of lubricants used for interface splines. The most commonly used greases are MIL-G-21164, MIL-G-3545, Plastilube Moly No. 3 with varying amounts of MoS_2 added, and Sundstrand 688272. It was reported that the higher concentrations of MoS_2 in greases are used for elevated temperature applications. Nonmilitary specification greases are sometimes used and are procured through the appropriate FSNs.

The Jacksonville NAVAIREWORKFAC reports that normally, when a part is reworked that is not assembled directly onto an airframe or accessory gearbox, no lubricant is usually applied to the spline. Sometimes a light oil may be applied to the splines prior to shipment to engine buildup or directly to a squadron. Several other NAVAIREWORKFAC(s) reported similar instances and most felt that a grease applied to the male or female spline would be contaminated by the time it reached its final destination. NAVAIREWORKFAC(s) report that it is the responsibility of the squadrons to follow their maintenance manuals for lubrication of the accessory spline prior to installation. In the case of the Lycoming CSDs, the Jacksonville NAVAIREWORKFAC reported that sometimes a light coat of Molykote No. 306X grease is placed on the male spline before the CSD leaves the NAVAIREWORKFAC. Perhaps the "bag-and-grease" technique used by American Airlines (see later) would insure that the same lubricant will be used by NAVAIREWORKFAC and squadron. In addition, grease contamination would be eliminated.

TABLE 18. LUBRICANTS USED

By Navy

*MIL-G-3545	*MIL-L-8937	MIL-L-7808	MIL-T-5624
*MIL-G-7187	*MIL-L-25681	MIL-L-23699	
*MIL-G-7711			
*MIL-G-21164			
*MIL-G-25537			
*MIL-G-81322			

*DAG 213 (Acheson Colloids)	*Pioneer 31 (Bendix)
*JH 13555 (Jack & Heintz)	*Plastilube Moly No. 3 (Warren) (FSN 9150-823-8045)
*Lubriplate 630-AA (Fiske)	*Plastilube Moly No. 3 (FSN 9150-889-3516)
*Molykote 306X (DC)	
*Molylube 503 (Bel-Ray)	

By Others (Additional)

*MIL-C-11796	*MIL-M-7866	MIL-L-5606
*MIL-G-23827	*MIL-L-46010	

*Anderol L-786 (Tenneco) (FSN 9150-926-1969)	*Plastilube Moly No. 3:	*688272 (Sundstrand) (FSN 9150-823-9049)
*Andok 260	+ 3% MoS_2	*922 B818-2 (Westinghouse)
*Moly No. 3 (SWGO)	+ 5% MoS_2	*FSN 204-040-755-3 (Bell)
*Molykote G (DC)	+ 50% MoS_2	
*Molykote 343 (DC)		
*Molykote 343X (DC)		

Asterisks (*) denote lubricants used for interface splines.
Brand names are cited as reported. They do not imply endorsement or otherwise by the authors.

NAVAIREWORKFAC engineers (Survey Form No. 209) point out that in the case of an AiResearch starter on a P-3 aircraft using a T-56 Allison engine, a variety of greases can be used as indicated in Table 19. This particular spline problem area has a high usage rate of 75 and 99 percent for the male and female splines, respectively. Obviously, the mixing of greases is not a recommended practice. Furthermore, it is quite possible that some of the greases are not as effective as others and the obsolete ones should be eliminated. American and United Airlines engineers report that no grease mixing is allowed on commercial aircraft. They further reported that the mixing of greases can be a contributing factor to accelerating spline wear.

In examining the large number of greases cited in Tables 18 and 19, the particular spline application should be borne in mind. Most interface splines are intended to operate in air environment only, thus greases of long induction period in air are desirable for such applications. On the other hand, some interface splines may occasionally be exposed to fuel; in that case a good wear life in fuel is also desirable and this may entail some compromise on the performance in air.

Several of the greases mentioned have been evaluated at SwRI. As shown in Appendix A, MIL-G-21164 has the longest induction period in air, while MIL-G-7711 (now obsolete), MIL-G-25537, and MIL-G-25537 plus 5 percent MoS_2 have moderate induction periods. MIL-G-27617 and Grease E (proprietary) have long wear lives in fuel; but have no induction period and thus very poor performance in air. MIL-G-81322 has not been tested at SwRI for spline application; but is reported by NADC to have a long induction period comparable to MIL-G-21164. Further, tests on MIL-G-81322 in an aircraft wing flap actuator application gave excellent results.*

Of the various military greases cited in Tables 18 and 19, MIL-G-3545, MIL-G-7187, and MIL-G-7711 are now obsolete and thus need not be considered. Of the remaining military greases, currently available results show that MIL-G-21164 (with a temperature capability up to 250°F) and MIL-G-81322 (up to 350°F) give the best performance in air. If occasional exposure to fuel is expected, MIL-G-25537 with or without 5 percent MoS_2 would represent somewhat of a compromise.

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*Tyler, J. C., "Performance Tests on Two Greases for Airplane Wing Flap Actuators," SwRI Rept. RS-524 (under Air Force Contract DAS 600-69-C-0294), October 16, 1968.

AD-A041 375 SOUTHWEST RESEARCH INST SAN ANTONIO TEX DEPT OF FLUI--ETC F/G 1/3
A CRITICAL SURVEY AND ANALYSIS OF AIRCRAFT SPLINE FAILURES.(U)
AUG 71 M L VALTIERRA, R D BROWN, P M KU N00156-70-C-2156

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TABLE 19. LUBRICANTS SPECIFIED FOR STARTER AND GEARBOX ON P-3 AIRCRAFT

Facility or Manufacturer	Recommended Lubricant	Spline Component Lubricated	Specifications and Comments
AiResearch	Not specified	Starter-male	-----
Alemeda	MIL-G-21164 or MIL-G-81322	Gearbox-female	Either can be used; however, MIL-G-21164 is usually used
Alemeda	-----	Gearbox-female and starter-male	Generally none is used
Allison	MIL-L-25681	Gearbox-female	NAVAIR 02B-5DE-6-2
Allison	MIL-G-81322	Gearbox-female	NAVAIR 02B-5DC-3 Use before installing cover
Bendix	Pioneer 31 or MIL-L-3545	Starter-male	-----
Hamilton Std.	MIL-G-21164	Starter-male	NAVAIR 03-105AA-19
Lockheed	MIL-G-21164	AiResearch, Bendix, or Hamilton Std. starters-male	-----
Squadrons (Navy)	MIL-G-21164	Starter-male	NAVAIR 01-75PAA-2-4.1 Used for most starters

Brand names are cited as reported. They do not imply endorsement or otherwise by the authors.

As to the numerous proprietary greases cited in Tables 18 and 19, no comments pro or con are warranted here. In any case, the list is far too large to manage, and an effort toward simplifying the list through systematic evaluations and stardadization with the objective of formulating suitable specifications appears worthwhile.

Equally important, development of greases with better in-air performance combined with acceptable in-fuel performance should also be considered.

As mentioned earlier, the commercial airlines do not allow grease mixing. This may imply a compatibility problem, which should be kept in mind in the formulation of new specifications.

2. Liquids

This lubricant category may include both oils and fuels. As explained previously, splines operating in oils generally present little problem, while those operating in fuels are still a matter of concern.

The types of liquids encountered in service are listed in Table 18. MIL-L-23699 and MIL-L-7808 type oils are usually used by the Navy and Air Force, respectively. These oils are most commonly used in the jet engines and in engine accessory gearboxes. Splines are lubricated with these oils whenever an oil mist or wet pad method of spline lubrication is used.

Some commercial aircraft use MIL-L-5606 hydraulic fluid in flap system gearboxes.

Splines in the jet engine fuel pump may be subjected to and lubricated by MIL-T-5624 type jet fuel. The splines operating within the fuel pump are usually not otherwise lubricated due to the possibility of contamination. In some cases, some type of surface treatments are used. Considerable work in this area is reported in Appendix A.

3. Solids

As shown in Appendix A, solid-film lubricants provide no protection against the severe wear conditions encountered in splines.

B. Lubrication Methods

Several methods are used in lubricating spline connections in current aircraft, namely, dry pad, mist, and wet pad.

1. Dry Pad

A large number of splines on current aircraft operate in an air environment without the use of any liquid lubricants. This type of spline connection is called a dry pad. The splines on the dry pad are usually lubricated with a grease with or without the use of a spline surface treatment. The main advantage of this method is that it does not require an elaborate lubrication system, hence it is used extensively for interface splines. The grease lubricated dry pad is normally relubricated at certain intervals, depending upon the life expectancy of the spline connection and/or the components involved. In the event that excessive spline wear cannot be minimized by the use of more effective grease and/or various surface treatments, the spline connection is sometimes converted to a mist or wet pad.

2. Mist

The terms mist and wet pad refer to the methods used in lubricating the interface splines of the engine accessory gearbox. The mist method (sometimes referred to as oil mist or oil spray) consists of providing small holes in the female splines on the gearbox to provide an oil mist to the splines between the accessory and the gearbox. Oil is originally provided by the engine oil recirculating system. Usually, no provisions are made to recover the oil mist and it is directed overboard. In the event that this technique does not adequately reduce excessive spline wear, a wet pad design will usually be recommended by the accessory or engine manufacturer.

3. Wet Pad

The wet pad design provides positive oil lubrication to the spline connection between the gearbox and an accessory. The high pressure (perhaps 10-40 psi) oil is directed from the gearbox to the spline connection, scavenged back to the gearbox, and recirculated at a very low rate. In order for the conversion to be made, the accessory male spline is usually fitted with a single or double "O" ring to prevent oil from entering the accessory. Current MS standards (MS 3325-3326) specify the gearbox and accessory pad designs for the wet pad lubrication system.

Conversion to the wet pad system is usually very costly when made for only one accessory, consequently the method is only used in severe cases that cannot be corrected by other means. The NATC will usually evaluate the wet pad improvement prior to full Navy usage.

C. Lubrication Interval

The majority of the spline connections used in military aircraft are lubricated at various intervals during maintenance and rework by squadrons and NAVAIREWORKFAC(s). The lubrication interval was reported to be specified by T. O. 's, NAVAIR's, PPB's, and other documents for various military aircraft. There is no one lubrication chart illustrating the lubricating intervals for interface spline connections on military aircraft.

The spline connection should be capable of performing properly so as to attain the scheduled OH time for the particular component or accessory. During NAVAIREWORKFAC or commercial OH, the spline parts will be examined to determine if the splines are below the rejection criteria, and if so, if the splines can operate satisfactorily for another tour. In some cases where severe wear has been noted, the lubrication interval will be reduced in an effort to insure proper operation up to the next NAVAIREWORKFAC overhaul.

Based on the limited information reported regarding spline history and the lubrication interval for the troublesome spline connections, it appears that the spline OH period and the accessory OH period are essentially the same. The TBO for the accessories varied from 400 to 3000 hours with the average being about 1250 hours. The lubrication interval varied from 60 to 1500* hours with an average of 640 hours.

The OH time is usually different for each aircraft; in addition, the OH time for each accessory can vary. The OH time for the majority of parts within the engine is usually much higher while some engine parts have mandatory retirement times.

D. Accessibility for Relubrication

As noted earlier, the majority of spline problems have been found to be at the interface spline connections between the engine accessory gearbox and a particular accessory. This spline connection can employ a dry pad, mist, or wet pad method of lubrication. In the dry pad spline connection, the accessory must be removed prior to relubrication. The mist or wet pad obviously does not require removal since oil is provided by the adjacent gearbox.

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*This lubrication frequency excludes a 3000 and a 4000 hour lubrication interval for Survey Form Nos. 176 and 177, respectively. In both cases, the spline life could probably be easily extended by reducing the lubrication interval.

The dry pad female splines at the engine accessory gearbox are not as accessible as the mating male splines on the accessories. The spline pitch diameters range from 0.4583 to 1.625 inches for the AND designed spline connections and 0.4583 to 2.000 inches for the MS splines. Since the splines are small in diameter, they are inherently difficult to clean and inspect.

In any event, it is important to clean the spline connection thoroughly to prevent any used grease and contaminants to carry over into the relubricated connection. Observations made during this survey indicates that the male and female splines at the accessory gearbox location are adequately cleaned during normal rework at the NAVAIREWORKFAC(s). At the depot maintenance level, essentially all of the splined parts on components are completely disassembled and cleaned and inspected.

E. Information from Lubricant Manufacturers

Information was obtained from Chevron Oil Co., Shell Oil Co., and Texaco, Inc., regarding (1) general recommendations, (2) current lubricants suitable for spline operation, and (3) suggested components for spline grease lubricants. This material was requested by means of the Lubricant Manufacturers Survey Form shown in Table 4, and summarized in Appendix C.

1. General Recommendations

Perhaps the most significant input from the lubricant manufacturers was the information obtained from the general recommendations which is summarized as follows.

The general feeling shared by all lubricant manufacturers is that a "soft grease" should provide good spline protection.* The grease should have good bleed or weeping characteristics thereby permitting a more oily substance to be available in the intimate spline connection. It was also suggested that the lubricant should not be contaminated and provisions should be made to contain the lubricant within the spline connection during operation.

Splines should be operated in a low viscosity oil bath whenever possible.

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*Work performed at SwRI under Navy sponsorship confirmed that in the case of Grease I (MIL-G-27617) and D (MIL-G-23549), the soft consistency of centrifuged samples provided more protection for the spline connection, with more scatter in the repeat test however.

Thick coatings or elastic films may be effective in retarding spline wear. A bonded type of elastomer may be capable of absorbing the relative motion between the mating parts thereby minimizing spline wear. *

Chevron engineers feel that consideration should be given to designing a spline grease pumping system minus the use of an external pump. This grease pumping concept is presumably used in automobile ball joints. The important factor is to insure that new grease comes into the intimate site of the mating splines thereby extending spline life. Ideally, the spline connection should be designed in such a manner as to provide this pumping action with provisions for a wear particle cavity and a new grease reservoir. This could allow the wear particles to be trapped and not permitted to recirculate with the newer grease.

2. Current Lubricants Suitable for Spline Connections

None of the companies contacted manufacture a grease specifically for spline connections. The general opinion is that the amount of grease utilized for spline connections is relatively small and therefore does not warrant a research and development program. The majority of the lubricant manufacturers will, however, strive to develop greases to conform to military specifications. Each of the lubricant manufacturers contacted suggested that the following lubricants may be suitable for spline connections:

Chevron	Shell	Texaco
Mobil No. 28 (MIL-G-81322)	Aeroshell 22 (MIL-G-81322)	Novatex 1 (MIL-G-21164B)
Krytox 240 (DuPont)	Aeroshell 14 (MIL-G-25537)	Regal Starfak 2 (Texaco)
	Aeroshell 17 (MIL-G-21164)	Uni-Temp 500 (Texaco)

Representatives of both Chevron and Texaco felt that the information requested regarding lubricant description and properties infringed on proprietary information, and therefore was not disclosed. The information contained in Appendix C, Table C-2 for Texaco was tabulated by SwRI personnel from literature furnished by Texaco.

* See Appendix A for SwRI work.

The Chevron Company is currently developing a polyurea-thickened grease to conform to MIL-G-81322, which they feel should be adequate for spline lubrication.

F. Information from Commercial Airlines

1. American Airlines

American Airlines did not report any spline failure problems. They are currently using the lubricants specified in Table 20 for a variety of spline connections. This tabulation indicates the estimated interface spline temperatures, the type of lubricant used, and the component OH period.

In order to insure that the correct grease is used and that contamination possibilities are eliminated, American Airlines utilizes a polyethylene bag containing the appropriate grease to be used. The male spline is lubricated after component OH for hydraulic pumps on the 707 and 727 aircraft. The bag-and-grease is attached to the component until the component is received in the field, at which time the grease is applied to the female spline connection to insure that the same grease is used. Since many American Airlines aircraft have wet pad connections, care is taken not to inadvertently use grease on a wet pad connection.

2. United Airlines

In March, 1969, United engineers consulted with other airlines to determine the type of lubricants used on generator interface spline connections. Table 21 contains information obtained relating to various lubricants used and corresponding field results. The majority of cases reported specified the use of some type of molybdenum disulfide.

The one interface spline problem reported by United was a generator to gearbox application on the DC-8 aircraft (Survey Form No. 214). United is currently using a 50/50 mixture of Uni-Temp 500 and Molykote "Z" powder plus Microseal 100-1 on the generator spline. The spline connection now incorporates a muff, and is sealed by means of an "O" ring to prevent contamination and provide lubricant retention. The results of this recent change are unknown at this time. The grease retention technique and muff was first used on a hydraulic pump by American Airlines (Survey Form No. 201, a trouble-free installation).

TABLE 20. LUBRICANTS USED BY AMERICAN AIRLINES ON SOME AIRCRAFT SPLINE CONNECTIONS

Spline Location	Component Manufacturer	American Airlines P/N	Aircraft	Spline Temp, °F	Type of Lubrication	Spline Lubricant	Component O.H., hr	Remarks
Hydraulic pump to gearbox	Vickers	PUM6651/ 5789	707, 727, BAC1-11	425	*Grease*	Molykote 343X	6400	Berulium Cu spline, w/a muff, silicone boot. *Grease has Teflon* particles. MTBR 1500 hr. Ref. Survey Form No. 201.
Starter to gearbox	AiResearch	STA6720 STA6052	707 727	425 425	Grease Grease	Plastilube No. 3 + 5% MoS_2	5000 5000	
Generator to CSD	Westinghouse	GEN6139	707, 727, BAC1-11	200	Grease	Uni-Temp 500 + 50% MoS_2	5600	Uses a pinned muff on end of dogbone spline into generator - Westinghouse recommended muff to reduce spline wear.
Auxiliary hydraulic pump to electric motor	New York Air *Brake Co.*	PUM6079	707, 727	150	Grease	Plastilube No. 3 + 5% MoS_2	6000	Unit in wheel well, small 3 gpm pump.
Generator to gearbox to CSD	Plessey (England)	TRA6963	BAC1-11	275	Oil mist	Enco 2380 Type II oil	7500	Mean time between removal 900 hr not due to bad splines; at 10,000 hrs splines have essentially no wear, will not require chrome flash buildup. Has concentric splines at gearbox and CSD location.
Hydraulic pump to gearbox	Vickers	PUM6134	747	500	Oil mist	Enco 2380 Type II oil	Remove on condition	Aircraft too new to evaluate spline performance.
Hydraulic pump to gearbox	Vickers	PUM6134	747	130	None	None	Remove on condition	37.5 h.p. pump. Aircraft too new to evaluate spline performance.
Air starter to gearbox	Hamilton Standard	STA6513	747	500	Oil mist	Enco 2380 Type II oil	Remove on condition	
Hydraulic pump to gearbox	Stratos-Fairchild	DR15003	747	130	None	None	Remove on condition	
Flap screw jack to electric motor	Vickers	MOT6111	707, 727	-40	Grease	Plastilube No. 3 + 5% MoS_2	Remove on condition	
Flap screw jack to electric motor	Vickers	MOT5260	707, 323	-40	Grease	*Plastilube* No. 3 + 5% MoS_2	Remove on condition	
CSD to gearbox	Sundstrand	TRA5000	747	275	Oil mist	Enco 2380 Type II oil	Remove on condition	Concentric spline drive. Oil mist from CSD unit.
CSD to gearbox	Sundstrand	6633	707, 727	500	Grease	Uni-Temp 500 + 50% MoS_2	12,000	
Fuel pump	CECO		707	350	Grease	Plastilube No. 3 + 5% MoS_2	11,500	Splines within pump are replaced at 11,500 hr. *Fuel pumps are sometimes* OH at 8000 hr. so splines can be repaired by chrome flash.

Splines are usually visually checked for excessive wear. 15% wear is the rejection criteria.
Splines within the gearbox may have as much as 25,000 hours. The splines are sometimes chrome flashed. The gearbox is usually OH at 16,000 hours.
Mean time between spline lubrication is 1500 to 2500 hours for all components.
Brand names are cited as reported. They do not imply endorsement or otherwise by the authors.

TABLE 21. LUBRICANTS USED BY VARIOUS COMMERCIAL AIRLINES FOR GENERATOR INTERFACE SPLINE CONNECTIONS

Airline	Current Lubrication	Results	Previous Lubricant	Results
Air Canada	Molykote M-88 dry film plus Silkoleen 751 (baked at 250°F for 30 min.)	No generator to CSD freezing. Treatment successful in reducing spline wear		
American	Aeroshell 14. (Stub shaft to spindle, Spindle to adaptor spline) 50/50 Mixture: Uni-Temp 500 plus Molykote "Z" powder (Adaptor spline to CSD coupling)	Working successfully. No recent experience of generator to CSD freezing		
Braniff	Molykote 343	No generator to CSD freezing.		
Continental	Aeroshell 7 (molybdenum disulfide compound)	Excellent generator to CSD units separate. O.K. after 4000 hr.		
Delta	Molykote 321 dry film plus 50/50 Mixture: Uni-Temp 500 plus Molykote "Z" powder.	Too early to tell -- started use on January 6, 1969.	a) 50/50 Mixture: Uni-Temp 500 plus Molykote "Z" powder b) Plastilube Moly No. 3 c) Molykote 343 (Hydraulic pump)	a) Generator to CSD freezing b) Excessive wear c) No good
Eastern	Aeroshell 5 (Evaluation on 50 B720/727 generators)	Too early to tell -- started use on January 21, 1969.	Aeroshell 14 (still in use)	Replaced 276 spline adaptors and 262 generator spindles in 1968 due to excessive wear and/or stripped teeth
Northwest	Molykote 343 (Aeroshell 5 plus 10% molybdenum disulfide plus 5% Teflon plus possible tackiness agent)	Very good -- only one case of generator to CSD freezing in 4 yr. Probably due to inadequate relubrication	a) 50/50 Mixture: Uni-Temp 500 plus Molykote "Z" powder b) Molykote 327 plus 50/50 Mixture: mineral oil base *grease plus Molykote* "Z" powder	Evaluation showed Molykote 343 superior to these two products
Pan-American	50/50 Mixture: Uni-Temp 500 plus Molykote "Z" powder	Two instances of generator to CSD freezing - otherwise O.K.		
TWA	Molykote G (mineral oil plus high percentage Molykote "Z" powder	Three generator to CSD freezings in past 2 years -- believed due to inadequate grease replenishment	Plastilube Moly No. 3 with 5% Molykote "Z" powder (used on hydraulic pump, water pump, etc., splines)	Grease loses fluidity after 1000 hr - requires replacement
United	50/50 Mixture: Uni-Temp 500 plus Molykote "Z" powder plus Microseal 100-1 on generator spline (Survey Form No. 214)	Six generator to CSD freezings in past six months	a) Plastilube Moly No. 3 (fuel pump) b) Microseal 100-1 plus plastilube Moly No. 3 (hydraulic pump) c) Microseal 100-1 only (hydraulic pump)	a) Very good b) Unsuccessful c) Working O.K.

Tabulation made on March 9, 1969 by United Airlines.
Brand names and results are cited as reported. They do not imply endorsement or otherwise by the authors.

G. Information from Airframe and Equipment Manufacturers

1. Boeing Company

The flap systems employed on several commercial aircraft are operated by means of gearboxes interconnected by torque tubes which transmit power to operate the flaps. In several cases, as illustrated below, MIL-L-5606 hydraulic fluid is used in many gearboxes, while MIL-G-21164 grease is used in others.

Aircraft	Lubricant	Approximate No. of Areas
737	Oil (MIL-L-5606)	8
737	Grease (MIL-G-21164)	5
747	Grease and oil (MIL-L-5606)	Unknown
727	Oil (MIL-L-5606)	All
707	Oil (MIL-L-5606)	All

The main reason for selecting the MIL-L-5606 hydraulic fluid as a lubricant for use in the gearboxes is its low temperature characteristics. At elevated altitudes the environment of the flaps can be as low as -40°F. The flap systems usually operate intermittently during take-off and landing operations. Various spline connections are used between the torque tubes and the gearboxes and are lubricated after 12,000 flight hours (approximately 20,000 flights).

2. Sundstrand Corporation

Sundstrand recommends only one grease for dry pad spline connections—namely, Sundstrand Part Number 688272 (50% Uni-Temp 500 plus 50% MoS_2. This grease is specified by FSN 9150-823-8049. Sundstrand has and is currently recommending to the airframe manufacturers that this type of lubricant be specified in the airframe manuals for dry pad spline connections.

Sundstrand performed a considerable amount of evaluation on this grease some eight to ten years ago. No other lubricants are now under evaluation. Sundstrand normally depends on the results obtained from commercial airlines regarding the effectiveness of lubricants and component operations through field representatives. Commercial airlines accumulate a considerable amount of time on various aircraft thereby providing a good input source regarding lubricant effectiveness.

Sundstrand feels that the military have too many lubricants for use in spline connections. It was recommended that either one or two lubricants be utilized for military interface spline connections without mixing lubricants.

VIII. MAINTENANCE PRACTICE

A. New and Used Splines

The performance of a spline connection on military aircraft is aggravated by the use of new and used male splines with new and used female splines. A new aircraft will indeed have all new mating spline connections. Through normal maintenance procedures, NAVAIREWORKFAC(s) and squadrons will remove and replace splined components when an aircraft is subjected to PAR, IRAN, CI, CER, CR, OH, QEC, SR, and on WO. During any of these times some of the splines can lose their original mating identity. No precautions are taken to keep the same splines together. At this time, a male or female spline is checked by E&E to determine whether or not it is within the specified limits. If the spline is within limits, it is usually reinstalled for another tour. In most cases when components are found to require new splines, no record is made of the replacements on the ARCs; therefore the exact life of the splines is unknown. In many cases, it would be essentially impossible to maintain the same mating splines since the male spline remains intact with the accessory while the engine and gearbox may be overhauled at another NAVAIREWORKFAC or a commercial rework facility.

The general consensus of personnel is that mixing of spline parts can have the following effects:

1. The mating of new and used spline parts will introduce higher tooth loads until some of the teeth wear down permitting nearly all of the teeth to share an equal load. The wear debris generated during this time remains dispersed throughout the grease thereby minimizing the beneficial effects of the grease and shortening the spline life.

2. It was also reported that the same axial engagement will not always be obtained within a spline connection thereby affecting the tooth load distribution and affecting the spline life.

3. Unusual wear patterns on a number of spline parts collected during this survey suggest that this was due to mixing of spline parts, some having nonuniform engagement. In many cases the original involute form is completely worn away. The unusual wear patterns can sometimes affect the spline wear measurement and rejection criteria.

B. Spline Misalignment Measurement and Control

Very little information regarding the misalignment of specific problem splines was obtained on the 91 spline problem areas.

The majority of these problems have involved interface splines that connect the engine or accessory gearbox to accessories such as starters, generators, hydraulic pumps, fuel pumps, etc. When two such components are connected by interface splines there are several sources of misalignment such as the stackup of tolerances of the many parts such as bearings, shafts, mounting pad, accessory flange, and the splines themselves. In addition, during operation or installation these parts may become bent or damaged resulting in misalignments in addition to those caused by the stackup of tolerances. Therefore, it appears very likely that many interface spline connections involve combined misalignment of the splines which is great enough to accelerate wear. However, the misalignment of splines assembled in components and accessories is seldom measured at the overhaul facilities as is shown by the responses from two Air Force, two Navy and one commercial airline overhaul facility which are given below:

1. Kelly AFB

According to personnel in the Mechanical Branch of Service Engineering Division, misalignment of the interface splines on accessories is not measured after the accessories have been overhauled and reassembled. Propulsion Branch personnel of Service Engineering reported that misalignment of interface splines on engines and gearboxes is not measured after these units have been overhauled and reassembled. Both branches reported that measurements of individual parts are checked against the tolerances of appropriate drawings and it is assumed that the installed unit will give satisfactory alignment.

2. Tinker AFB

Service Engineering Division personnel reported that spline misalignment on assembled accessories is not generally measured. Misalignment is controlled through tolerances on parts. Personnel have experienced spline misalignment problems with newer constant-speed drives (CSD's). In order to solve this problem, quick attach-detach mounting plates are used between the mating CSD and generator. One aligning plate is set in epoxy and attached to the CSD. Alignment is made by means of a dial indicator after which the epoxy is allowed to set. The same procedure is used on the generator with another aligning plate and the generator is then attached to the CSD.

3. Quonset Point NAVAIREWORKFAC

Aerospace Engineering Powerplant personnel reported that misalignment on assembled units such as engines, gearboxes, and accessories is not generally measured. One exception is the J-65 engine gearbox. Spline misalignment is checked on this gearbox because misalignment problems have been encountered with each interface spline on the gearbox, necessitating considerable rework.

4. Pensacola NAVAIREWORKFAC

According to Powerplant and Accessory personnel, spline misalignment is generally not measured on assembled accessories, engines, or gearboxes. Parts are measured to check conformity with appropriate drawing tolerances. Shafts are checked for straightness, and bearing bores are checked for fit and concentricity. On the basis of these operations, alignment of the installed accessory is assumed to be within the original limits.

5. American Airlines

Personnel from Aircraft System Engineering reported that misalignment of interface spline connections is normally not measured. The airline had experienced a severe interface spline problem at a hydraulic-gearbox connection. The misalignment of the female spline at the gearbox was checked out and found to be in excess of the AND Standards by a factor of 2 or 3 to 1. The problem was alleviated by improving the alignment, resulting in extending the life of the spline from about 400 hours to more than 6400 hours.

C. Spline Wear Measurement

In the manufacture of new splines, the accuracy of production is checked by routine quality control procedure. The new splines can be checked with SAE standard gages of the types listed below:

- Pins (or wires)
- Composite spline gage having a full complement of teeth
- Sector spline gage having two diametrically opposite groups of teeth
- Sector plug gage (paddle gage)
- Sector ring gage (snap ring gage)
- Progressive gages (Go and No-Go type)

The pin (sometimes called wire) method of checking tooth thickness or spacing, based on a true involute profile, is well accepted

in industry. Procedures and tables are prescribed in the SAE Handbook. The method is also widely used to measure spline wear; but its validity needs careful study. Worn teeth do not normally retain a true involute profile, so use of the standard tables can lead to errors. Moreover, if wear does not occur uniformly over the entire tooth length, the pins will misalign and the measurement can be misleading.

During the current survey, it was noted that many different methods are being used for measurement of spline wear. In many cases, NAVAIREWORKFAC personnel feel that the currently used gages are not sufficiently accurate, can only be used on one spline size, are too expensive and difficult to use, and are not always capable of measuring spline wear by virtue of the resulting wear patterns. The Ground Support Division of NAEC is currently studying the methods of measuring spline wear. It is understood that a report will be forthcoming containing information relating to the various spline sizes utilized in Navy aircraft engines.

The various wear measurement techniques are listed in Table 22 and discussed below:

1. <u>Backlash</u>

The Avionics Department of the Cherry Point NAVAIREWORKFAC reported that visual inspection is usually used to determine whether acceptance or rejection of splines is indicated. Sometimes, while the splines are engaged, one spline is rotated back and forth (essentially a backlash measurement) to determine if the spline connection is suitable for use. No specific rejection criteria was cited.

2. <u>Ball, Dial-Indicator</u>

United Airlines normally measures the front compressor rear hub spline by means of a dial-type ball gage, Model No. 202P-232W-17824, manufactured by Federal Gage, Providence, Rhode Island. The gage observed contained a dial calibrated from 0 to 20 thousandths of an inch in 0.005-in. units and cost approximately $1,000. Different length ball-stem adapters can be utilized so that various size female splines can be measured. This instrument is used primarily for engine splines.

3. <u>Comparator, Optical</u>

The Cherry Point NAVAIREWORKFAC also uses an optical comparator. This device is similar to a microscope having a 10 and 20 power lens. The worn spline is placed in the holder and

TABLE 22. SPLINE WEAR MEASUREMENT TOOLS USED

Measurement Tool	By Navy	By Others
Backlash	1	-
Ball, Dial-Indicator	10	2
Comparator, Optical	5	-
Comparator, Pocket	1	-
Depth Gage	1	6
Door Knob	4	-
Feeler Gage	-	1
Go-No-Go	2	4
Micrometer	-	1
Pins or Wires	26	23
Photographs	1	-
P&W Tools	-	2
Shadowgraph	1	4
Stylus	-	1
Versa-Dial	1	1
Versa-Dial w/Q. P. Tip	16	-
Vinco Gage	1	-
Visual	13	11
Not Specified	-	2

viewed through a rubber eye protector. The enlarged spline is seen with a scribed calibration scale in inches. A visual reference with the calibration scale is made and the amount of spline wear noted. It would appear that a spline replica would have to be made and sectioned for effective measurement.

4. Comparator, Pocket

Pensacola engineers reported that a pocket comparator was used to measure generator spline wear in accordance with NAVWEPS 03-5AA-100.

5. Depth Gage

ARADMAC utilizes a conventional micrometer type depth gage with a pointed stylus to measure the spline wear and pit depth on the helicopter main rotor mast splines.

6. Door Knob

Approximately ten years ago, engineers at the North Island NAVAIREWORKFAC designed a backlash-type spline wear measuring tool for both male and female splines commonly known as the "door-knob". This relatively simple device is illustrated in Figure 5. Part Number NAS NI T32512 was noted for the particular gage reviewed. In this device, the knurled knob is attached to the inner tube containing a short length (1/8-in) spline. Another identical spline was affixed to the outer tube attached to the stationary member. As the door-knob splines are placed into a female spline, the knurled knob is rotated and the spline wear is indicated on the dial. A separate tool is required for each male and female spline having different pitch diameters. A similar type gage was made for measuring male splines. This unit was graduated in one-thousandths of an inch up to 0.015-in. The design concept is essentially the same as the Vinco Gage (Item 17).

7. Feeler Gage

ARADMAC utilizes a conventional feeler gage to measure step wear on a quill spline shaft located in the engine transmission on a CH-47 helicopter. Presumably, a feeler gage of appropriate size is placed into the wear step and matched with the unworn portion of the spline tooth to determine the amount of wear.

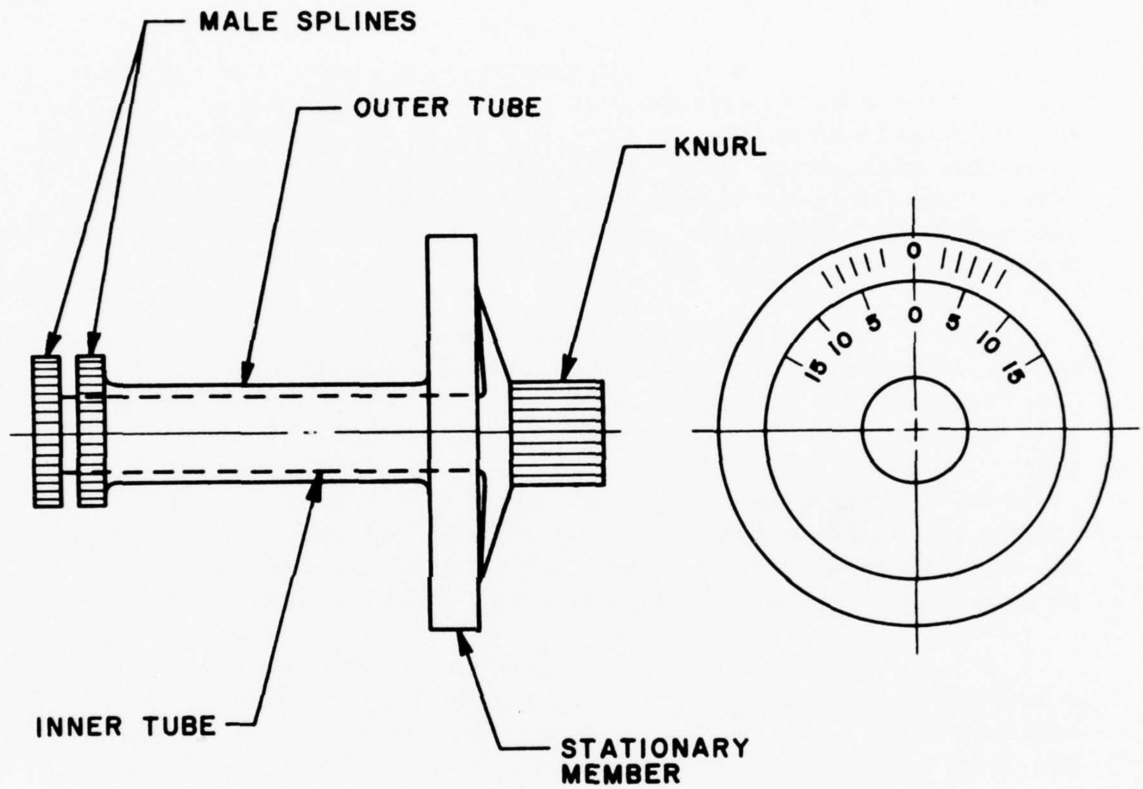


FIGURE 5. "DOOR-KNOB" SPLINE WEAR MEASURING TOOL

8. Go-No-Go Gages

Technical Orders and NAVAIR's normally specify easy-to use gages for use at squadron levels for measuring spline wear. Navy NAVAIREWORKFAC and Air Force Depot maintenance bases usually use more sophisticated tools. Information was obtained on the following go-no-go gages:

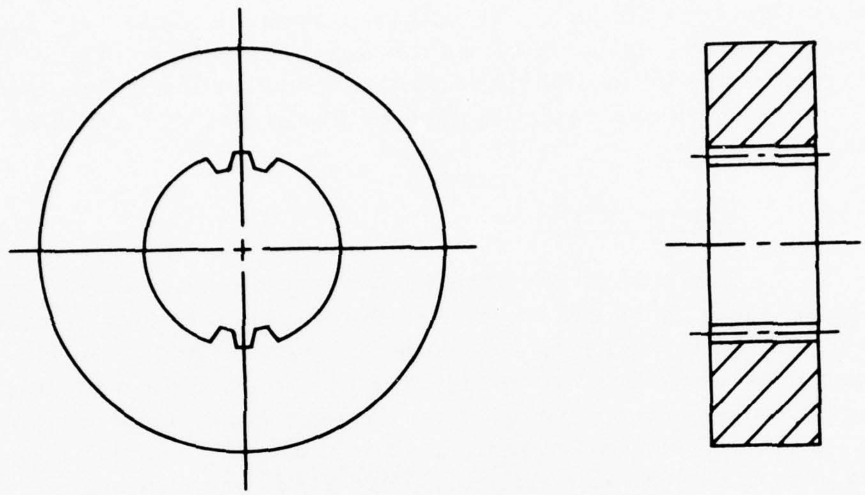
a. A ring type go-no-go gage is used at squadron level for accepting or rejecting spline wear on male splines. The one tool examined was designated GDN-5230 T-16, as illustrated in Figure 6A. This gage utilizes four oversized (wider) spline teeth. Most spline connections are designed so that the male spline is in full contact with the female spline, consequently this tool would be effective for most measurements.

b. Some squadrons use go-no-go gages similar to that illustrated in Figure 6B for measuring female splines. One tool examined was designated GDN 5229 TT0956. This tool utilizes four oversized (wider) spline teeth. The gage would not be effective unless the end of the female spline teeth were worn so that the tool could be inserted to the worn area. Many of the female gearbox splines examined did not receive wear at the end of the female spline. Go-no-go gages of this type were used at the Kingsville NAS for checking female splines on the inline CSD (Survey Form No. 170).

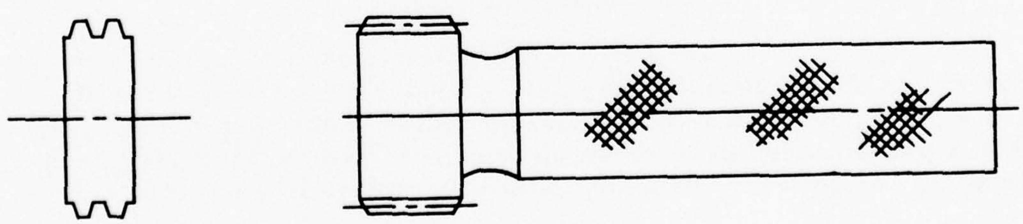
c. United Airlines utilizes a go-no-go type gage consisting essentially of a small tee-handle with a ball attached to each end of the tee. The gage is tilted into a female gearbox spline and if the handle can be placed coincident with the center line of the female spline, the spline is rejected. A separate tool is required for each different spline pitch diameter. The tool has the capability of being placed into the wear area, even if the end of the spline is not worn.

d. United Airlines also utilizes another type of go-no-go gage on the female spline at the gearbox. This tee-handle gage has the male spline having a 20 percent greater tooth width. Once 20 percent of the female spline has worn off, the gage will slide into the female spline rejecting the female spline. The end of the female spline must be worn for effective use of the gage.

e. United Airlines utilizes a similar device for the male spline. A thin plate is made having a cut-out of a female spline. The cut-out is made so as to represent a female spline having oversize (wider) teeth. Once the male spline wears so that it can pass into the female go-no-go gage the spline is rejected.



A. MALE SPLINE GAGE



B. FEMALE SPLINE GAGE

FIGURE 6. GO-NO-GO GAGES USED BY SQUADRONS

9. Micrometer

American Airlines utilizes a standard micrometer to measure spline wear on Vickers hydraulic pump splines as specified in Vickers Overhaul Manual. The measurement is made over four spline teeth and five spline teeth on the dog-bone spline. Once the measurements are below specified values in the Vickers Overhaul Manual, the splines are rejected (Survey Form No. 201 and Appendix E, Item 8c).

10. Pins or Wires

Table 22 shows that pin or wire measurements are used most frequently by the Navy and others. To measure a male spline, pins of specified size are placed between opposite spline teeth, and measurements are made over the pins with a micrometer or other suitable device. Three pins are sometimes used for small splines. Female splines are measured in a similar manner utilizing two pins and an inside micrometer. Three pins are sometimes used with a plug gage. The technique is called under-the-pins, or between-the-pins measurement. The measurement of the female spline is usually more difficult to accomplish.

As noted earlier, the pin method for measuring wear should be employed with caution. The reasons are as follows:

a. Involute Profile

The worn teeth seldom preserve a true involute profile. Therefore the standard tables can lead to errors which may be important in critical applications.

b. Nonuniform Tooth Wear

The majority of splines inspected during this program exhibited nonuniform wear. Usually the worn spline will have a pivot point somewhere near the center of the spline length. When a pin is placed between an unworn and worn tooth, it may rock backward and forward resulting in an inaccurate measurement.

AiResearch specifies that "when measurement over wires is not feasible due to the local nature of the wear, one or both wires must be replaced by a ball of the same diameter as the wires."

c. Pins Too Long

In many cases the under-the-pin measurement cannot be performed if the pin length is longer than the worn portion of the spline. Spline connections are usually designed so that 100 percent of the male spline is used in contact with the longer female spline. It is thus possible for the pins to ride over the worn section of the spline, yielding in effect a measurement of the unworn portion. The pin method can also be ineffective on the male spline unless the full length of the tooth is worn.

A variation of the pin technique is to employ balls in place of pins. When balls are used, the tooth profile error mentioned above still remains.

11. Photographs

Norfolk engineers had a severe spline problem with the P-2 flap actuators and spline drive system some time ago. This aircraft utilized a Varicam drive which was attached to about nine spline connections between various rotating shafts, gearboxes, and universal joints. Photographs of Varicam drive splines were taken at various worn conditions and labeled: New, Serviceable, Marginal, and Unserviceable. This photographic technique enabled the squadrons to accept or reject splines (Ref. P-2 Airframe Bulletin No. 51, 25 May 1966).

12. Pratt and Whitney Tools

Tinker Air Force Base reported utilizing P&W tools 17286 or 17401 for measuring spline wear at the gearbox on J-57-43 and -59W, TF-33-P9, and P3 engines. No other description was available.

13. Shadowgraph

Cherry Point engineers utilize a shadowgraph (manufactured under the trade name MicroVu Model No. 400, Serial No. 5920, Burbank, California), for some spline measurements. A sectioned plastic replica of the worn spline teeth is placed in an appropriate holder. A beam of light is then passed across the spline replica, amplified, and projected onto a ground glass screen. Engineers generated an involute tooth form on a piece of clear plastic which is positioned onto the screen. By visual comparison from the involute tooth form and the graduations on the screen, an accurate means of determining the amount of wear can be obtained.

This device, although costly, is considered to be very good and accurate and is used where accuracy is considered important. The worn splines on the J-48 engine utilized on the H-46 helicopters are measured by this technique as specified by NAVAIR 03-95A-26, dated 15 May 1970.

ARADMAC engineers utilize this technique for spline wear measurement on CH-47 helicopters engine transmission splines (Survey Form Nos. 136 and 137).

14. Stylus

Sundstrand utilizes a metallic stylus as a visual technique for measuring excessive spline wear. The stylus, resembling a pencil, has a diameter at the pointed end of about 0.030 in. The stylus is placed in the worn spline step and an indication is obtained as to the amount of spline wear present. This is similar to the feeler gage previously described.

15. Versa-Dial Type Gage

Quonset Point engineers reported that this type of gage was manufactured by an aircraft engine vendor, and resembled that illustrated in Figure 7. The gage is designed so that one of the arms is free to move up and down by means of guides, and is activated by a trigger mechanism. At the end of each of the arms, balls were used (simulating an over-the-balls measurement). A geared mechanism was provided which rotates the dial as the arms are allowed to move relative to each other. A curve was provided relating the dial indicator reading versus the amount of wear. Measurements were made on worn splines and compared with the curve.

16. Versa-Dial Gage with Q. P. Tips

Quonset Point engineers have incorporated square tips (Q. P. Drawing 42330-C) in place of the balls on the two arms of a Versa-Dial gage (manufactured by Standard Gage Company, Poughkeepsie, New York). A standard gage block is used to set the gage for a specific size spline. The trigger is depressed allowing the arms to move closer together so that the tips can be installed in a female spline. The trigger is then released and the needle will indicate "accept" or "reject". This device cost approximately $1,200. It can be reset for other size splines; however, this is not normally accomplished in the course of routine spline measurement, therefore requiring a large number of gages for a variety of male and female splines.

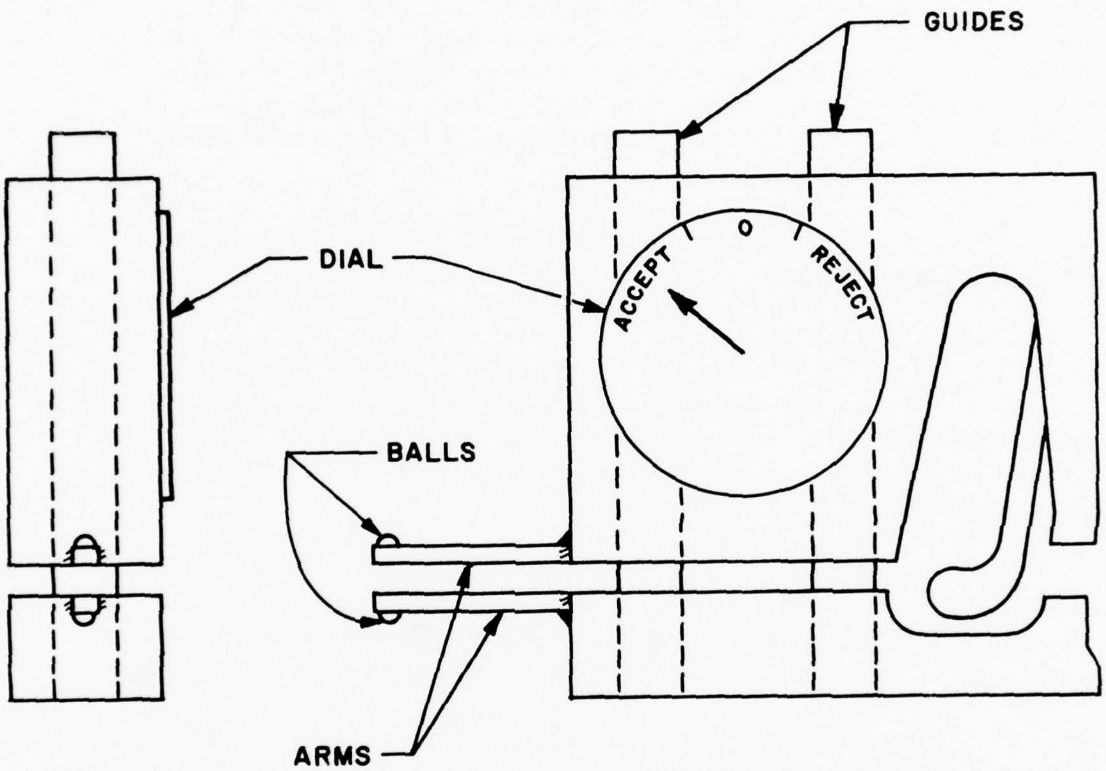


FIGURE 7. VERSA-DIAL TYPE GAGE

17. Vinco Gage

This gage consists of a fixed and movable spline probe (about 1/8 in. long spline teeth) which contacts the unworn involute surface and the worn surface at the pitch diameter. A direct wear reading is obtained by rotating a lever on the gage. The measurement is said to be linear and is reflected on a dial indicator. The manufacturer claims an accuracy of 0.0002-in. A separate gage is required for each different male and female spline pitch diameter. The Vinco gage for the male spline, VCO No. 76-887-00-00 (FSN RX 5220-132-1287FQ7X), costs approximately $900. A vinco plug type gage for a female spline, VCO No. 76-675-00-00 (FSN RX 5220-132-1285FQ7X), costs approximately $1,500.

North Island engineers utilize Vinco gages for some of their measurements.

18. Visual

As illustrated in Table 22, the second most popular method of examining spline wear is by a visual means. It was also noted that in many cases, this method was used to determine "a few thousandths of an inch" of wear.

American Airlines normally utilizes visual inspection of the spline connections as a criteria for spline replacement, particularly for accessory splines. The consensus is that in most cases, it is more costly to measure a spline than it is to replace it.

Kelly Air Force Base utilizes visual rejection techniques along with other methods. In many cases the visual rejection technique is closely related to the rejection criteria. For example, a sophisticated tool is not required to measure 50 percent of the remaining tooth land for rejection.

Cherry Point engineers utilize visual inspection for acceptance or rejection of a large number of splines. In many cases the component manufacturer will specify how much tooth wear is acceptable, however, no spline measuring device will be recommended.

D. Spline Rejection Criteria

In most cases the rejection criteria for individual splines is specified in NAVAIR and T.O. manuals. Commercial airlines obtain this information from the aircraft maintenance manuals prepared by the airframe manufacturer which contain recommendations from the accessory and engine manufacturers.

The rejection criteria specified has a significant effect on the replacement rate of the splined part. It is desirable to set the rejection criteria in such a manner as to obtain the scheduled overhaul time of the component. At the overhaul time, a decision must be made as to whether or not the part will be suitable to attain the next overhaul without failing.

Table 23 illustrates the different spline rejection criteria reported in the survey. In the vast majority of the spline connections investigated in the survey forms, a few thousandths of an inch was specified as the rejection criterion. Various wear measuring techniques such as pins, balls, shadowgraph, and other special tools and gages were used in conjunction with a few thousandths of an inch rejection criterion. However, the use of pins for such an application has previously been questioned, despite its simplicity and low cost. Interestingly, in 14 of the times that visual inspection was specified, the rejection criteria of "a few thousandths" was also specified.

It was reported that in the majority of these cases, the rejection criterion of a few thousandths of an inch is directly related to the case thickness of the spline part. The general feeling is that once the case thickness is exceeded, the spline will begin to wear at a more rapid rate. However, it should be noted that the AND standards do *not* specify case thickness for the male splines, and the MS standards do not specify case thickness for either the male or female splines.

The spline rejection criteria was found to divide into another more liberal group, from 10 percent of the tooth land to a knife edge. Survey forms indicated that the criteria was divided into the 10, 20, 33, 50, and 90 percent of the tooth land to a knife edge (or when the top land dimension reaches zero). These rather liberal rejection criteria are measured visually and specified for male splines on some starters, generators, hydraulic pumps, and oil pumps. Based on the information obtained from the drawings regarding case hardness and thickness, the 10 percent criterion appears to be related to the case thickness of the male spline. The other rejection criteria for male splines are probably related to through hardened materials.

In a limited number of cases, the individual's discretion is used for rejection of splines—no specific criteria was cited. Survey forms revealed that this was specified on some hydraulic pumps, fuel pumps, and on a wing shaft damper used on a helicopter.

It was reported that no rejection criteria were specified in only two problem areas. These refer to two starters (Survey Form Nos. 197 and 228), and one female connection for a generator on an APU (Survey Form No. 223).

TABLE 23. SPLINE REJECTION CRITERIA USED

Criteria	By Navy	By Others
Few Thousandths of an Inch	57	38
10% of Tooth Land	8	1
20%	1	1
33%	2	-
50%	-	3
90%	3	-
Knife Edge	1	-
Individual Discretion	1	4
Not Specified	2	-

IX. STATE OF THE ART

A. Magnitude of Spline Problem

As mentioned in Chapter I, a typical single-engine naval aircraft employs 174 toothed spline units not counting those located strictly within accessories, and a multi-engine aircraft may well employ more than 200 such units. It was also pointed out in Chapter V that spline failures currently affect the reliability and maintenance of 40 percent of the Navy's fixed wing aircraft types and 70 percent of the Navy's rotary wing aircraft types—or 45 percent of the Navy's aircraft types overall. Clearly, the magnitude of the spline problem cannot be lightly dismissed.

The very large number of spline units used on aircraft reflects weight, size, system complexity, and initial cost considerations. The large number also may, though not necessarily must, mean a high probability of failures. Aircraft reliability and readiness cannot be measured in terms of dollars and cents. However, in evaluating the direct cost effectiveness, the initial cost is only one factor which must be considered together with the cost of servicing, repairs, and replacements. On balance, spline units enjoy extreme weight and size advantages. Other known means of drives all entail weight and size penalties so that they cannot be realistically considered unless splines definitely cannot do the job. The results of this survey have not established that this is so. On the contrary, the authors have come to the inescapable conclusion that in most cases of early spline failures, these are the results of inadequacies of design, lubrication, and maintenance practices, rather than the basic unsuitability of the splines as such. It is believed that much can be done to improve the reliability, extend the life, and reduce the total cost of operation of splines. These matters will be discussed later in this chapter in terms of the ongoing work learned during the survey. Specific recommendations on improvement programs and on technology gaps which need to be closed will be summarized in the two chapters which follow.

The reliability of spline connections is intimately related to their locations or applications. General conclusions are as follows:

1. Splines located inside the engine or gearbox generally exhibit minimal wear. These splines generally receive intermittent or continuous oil lubrication. Although these splines usually operate at moderate to heavy loads, their successful operation is primarily due to the presence of oil lubrication.

2. Splines located in the airframe generally exhibit minimal to moderate wear. These splines are used in applications such as flaps, slats, and trim actuators which are subjected to intermittent operation and light to moderate loads. These splines are usually grease lubricated. The most significant factor enhancing the life of these spline connections is that they operate only intermittently.

3. Interface splines, which connect two components, have provided the majority of the wear problems found in this survey. These splines are used primarily in connections between the engine accessory gearbox and such accessories as CSD, CSDS, fuel control, fuel pump, generator-alternator, hydraulic pump, oil pump, or starter. Other interface spline problems are also encountered on engine to shaft power, shaft power to gearbox, shaft power to CSD, main rotor mast, 90° tail shaft, propeller hub, etc. Interface splines are usually grease lubricated. Their difficulties are due primarily to sustained operation at moderate to heavy loads, often at high rotational speeds.

Since the majority of the spline problems are associated with the interface splines, it is evident that the interface splines merit special attention. In what follows, interface splines will thus form the primary basis of the discussions.

B. Corrective Actions

The problems that exist with interface splines are well recognized by the personnel of the Navy and other organizations contacted. A number of corrective actions have been taken or proposed at different operational levels, though many of these are apparently not well coordinated on a service-wide basis.

Table 24 summarizes the number of reported current and proposed corrective actions on interface spline problem areas by the Navy and others. The organizations contacted have not all indicated whether corrective actions have been taken or proposed, or else not considered. However, it is significant to note that among those Navy organizations that have answered the query, no appropriate action has been taken in 55 percent of the cases. This compares with 13 percent of inaction as reported by the other organizations.

C. Current and Proposed Improvement Programs

Table 24 shows an alphabetical listing of the various techniques considered in the current and proposed improvement programs reported for interface spline problems. These and other component improvement programs are described in Appendix E. The component improvement

TABLE 24. REPORTED CURRENT AND PROPOSED CORRECTIVE ACTIONS ON INTERFACE SPLINE PROBLEM AREAS

Corrective Actions	By Navy	By Others
Current	8	9
Proposed	6	12
None	17	3
Corrective Techniques		
Alignment	3	4
Crowned Spline	-	1
Cut and Replace	4	9
Grease	4	2
Hardness	3	1
Material	-	2
Muff	7	6
Oil Mist	5	1
Plating Repair	3	-
Redesign	6	7
Research Program	1	1
Seal	2	8
Surface Treatment	1	8
Wet Pad	4	8

programs in Appendix E provide information relating to the components involved with an abstract as required by the work statement. Much of this information is in the form of AYC, CIP, DIR, EBN, ECP, EIR, EPN, LES, PPC, PPB, SEO, WO, and WRs.

From Table 24, it is evident that the majority of the Navy's corrective techniques involve the incorporation of a spline muff, oil mist, spline redesign, spline repair (cut and replace), improved greases, and the wet pad. Techniques considered by the others concentrate more on spline repair (cut and replace), incorporating spline muff, grease seal, surface treatment, and the wet pad.

Details of the various current and proposed improvement programs are summarized in Appendix E. Typical examples are given below:

1. Alignment

Reports indicate that the runout of J-65 fuel and hydraulic pumps were checked; see Appendix E, Item 6b. Information obtained from NATC revealed that testing of CSD Self-aligning shafts was being performed; see Appendix E, Item 16. Currently, Kelly and Tinker engineers are measuring and alleviating misalignment problems on a power transmission drive shaft coupling, i. e., shaft power (Survey Form Nos. 112 and 236), and on a low replacement (17 and 15 percent) CSD engine-gearbox problem (Survey Form No. 194).

2. Crowned Spline

In some non-Navy applications, the male spline is crowned to permit the acceptance of more misalignment within the spline connection. Kelly engineers (Survey Form No. 99) propose to crown the male spline on a generator-gearbox problem, while Sundstrand is considering crowning all of the CSD male interface splines. AiResearch utilizes crowned splines in many of their applications, and will probably do so in the operation of the AiResearch fuel pump (Survey Form Nos. 161 and 218; and SwRI Research Program, Appendix E, Item 15).

3. Cut and Replace

In some instances, NAVAIREWORKFAC shop personnel collect expensive splined parts hoping that engineering will develop a cut and repair fix. The major factors involved in repair over replacement are availability of new parts, cost of the new part, and cost of repairing the old part. The female spline extending through the gearbox will invariably be the more expensive of the two spline parts. This repair technique was reported by the following:

Facility	Form No.	Location	Remarks
Alameda	208	Propeller hub assembly	
Jacksonville	189	Spline within engine	Appendix E, Item No. 5b.
Quonset Point	180	Hydraulic pump-oil pump	
Quonset Point	182	Hydraulic pump-oil pump	
Tinker	199	Gearbox for fuel pump	
ARADMAC	129	Starter-generator spline	
ARADMAC	132	Starter-generator spline	
ARADMAC	133	Starter-generator spline	
ARADMAC	134	Generator	

Alameda engineers are currently repairing the propeller hub assembly (Survey Form No. 208) by machining off the spline boss and using a spline adapter configuration.

The female spline (Survey Form No. 180) within the oil pump on the A-13 and RB66 aircraft utilizing a J-71 engine has been repaired by Tinker engineers. They have refurbished 116 of these shafts, typical of that illustrated in Figure 8. The female spline was made by electro discharge machining (EDM). This process, not usually used by the aircraft industry, is a very accurate method of spline fabrication. Male threads were provided on the EDM female spline so that it could be screwed into the remaining shaft. Once in place, the female spline was welded, salvaging the entire shaft.

The expensive female spline (Survey Form No. 182) on the gearbox of a J-79 engine used on the F-4B, F-4J, RA-52, and the F-104 is being repaired by Quonset Point engineers. The female spline shaft is machined off and a new spline insert is welded in place.

Tinker engineers (Survey Form No. 199) propose to cut off the female spline used on the J-57 engine for the B-52 and KC-135, and replace it with a sleeved spline that would be electron beam welded in place.

ARADMAC engineers (Survey Form Nos. 129, 132, 133, and 134) report reworking male splines on starter-generator and generator applications for the T-53 engine used on the UH-1B, C, D, F, and H helicopters. The fix is accomplished by machining off the spline teeth and utilizing a spline sleeve over the armature shaft and pinning it in place.

4. Greases

The variety of greases currently used by the Navy and other organizations are listed in Tables 18 and 19, and discussed in some detail

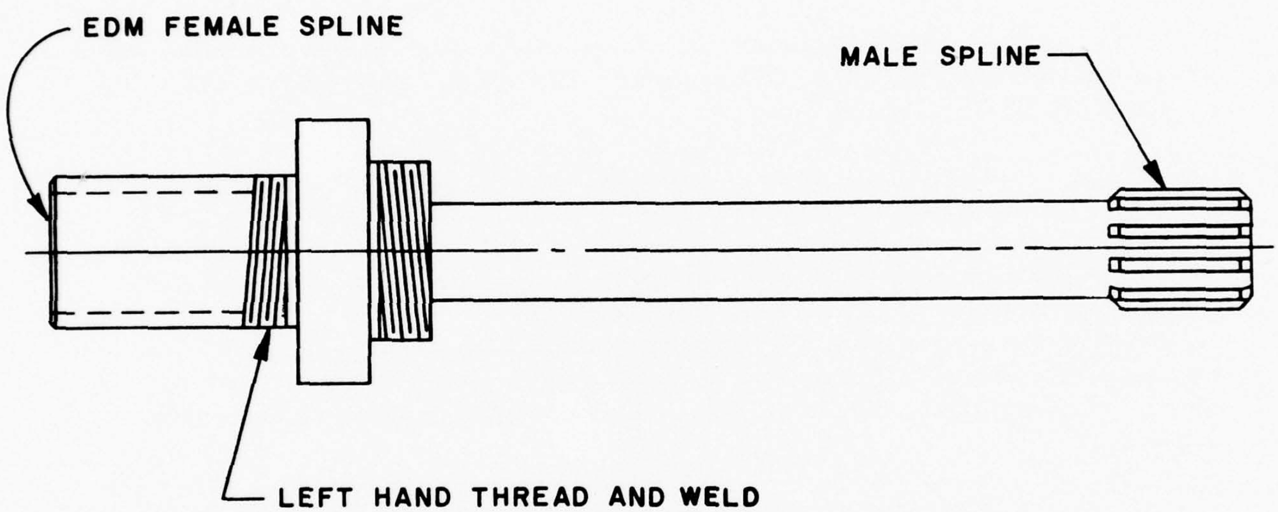


FIGURE 8. REPAIR OF SPLINE SHAFT USED ON HYDRAULIC-OIL PUMP

in Chapter VII. In addition, there has been much discussion about improved greases and their possible constituents or characteristics (see, for example, Appendix C).

The large number of greases listed in Tables 18 and 19 present a baffling problem to the maintenance personnel. Many of these are called out in military specifications; but several (MIL-G-3545, MIL-G-7187, MIL-G-7711) are obsolete and should be withdrawn from the inventory. Others are available by FSNs or by brand names, apparently without the benefit of systematic evaluation or control. There is an urgent need to consolidate all these listings, initiate a program of systematic evaluations, and compile a unified series of military specifications to cover various applications.

5. Hardness

Cherry Point engineers are currently making the female spline (Survey Form No. 220) harder on the aft transmission gearbox for the H-46 helicopter.

Jacksonville engineers are currently changing the hardness requirements on splines operating in a fuel pump (Survey Form No. 171) in an effort to extend spline life. These splines operate within fuel and are normally repaired by a chrome flash specified by NAVAIR 03-110DAA-17.

Additional considerations may be found in Chapter VI.

6. Materials

AiResearch engineers are studying the use of superior materials (Survey Form No. 162) used in an APU for the F-27 and F-28 aircraft. Currently, drawings for the mating parts specify the same material, AISI 4340, for the male and female splines.

Additional information is presented in Appendix A and Chapter VI.

7. Muff

The photograph in Figure 9 illustrates a typical spline muff used on a current problem area (Survey Form No. 199, Tinker) before and after excessive spline wear. The muff may be described as a cylinder having female splines within the cylinder and male splines on the outside. The muff is generally used between the male accessory spline and the female spline on the accessory gearbox. The muff is held in place over the small male accessory spline by means of a snap ring or pin. Its primary function is to allow the spline connection to accept more

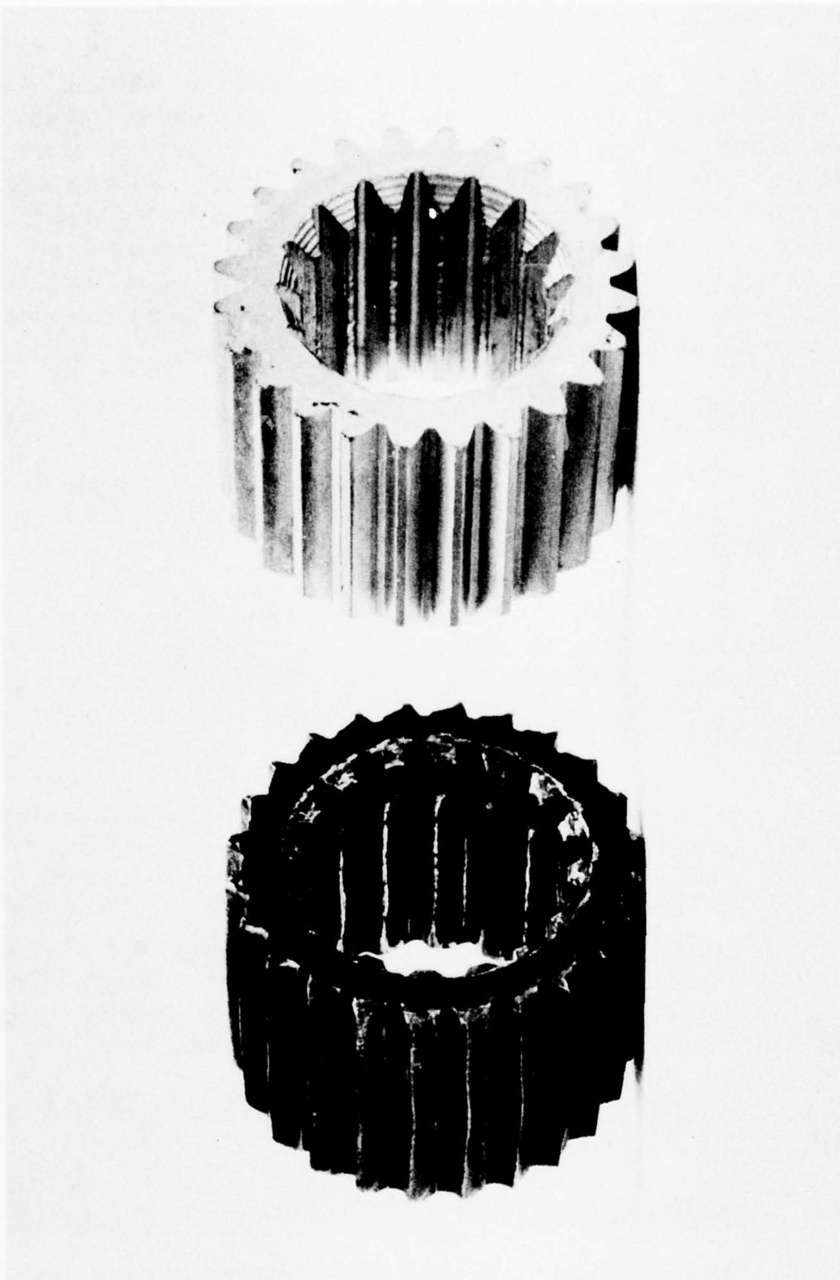


FIGURE 9. TYPICAL SPLINE MUFF BEFORE AND AFTER EXCESSIVE WEAR
(Survey Form No. 199, Tinker)

misalignment. The muff is being used by many accessory manufacturers for use at the interface spline connection to the gearbox and in some cases within the accessory itself. Since the muff is considered a part of the accessory, the accessory manufacturers have control of its design. This will be particularly true for new splines made under the MS standards which do not specify spline materials and provide that the case hardness should be greater than Rockwell C 56. In the AND standards, the material selection is left up to the discretion of the designer.

During the course of this survey, information was collected from various sources regarding component improvement programs. A tabulation of the spline muff information obtained from various facilities is listed below:

Facility	Survey Form No.	Remarks
Alameda & Jacksonville	207	Proposed for Lycoming CSD, see Appendix E, Item 6e.
American Airlines	201	"Trouble-free installation". Uses muff, Molykote 343X and boot seal, see Appendix E, Item 1.
North Island	229	Specifies muff for fuel pump, see Appendix E, Item 14.
Quonset Point	181	Proposes muff for oil pump to hydraulic pump on J-71 engine, see Appendix E, Item 7c.
Tinker	199	Tried Plastilube Moly No. 3 now oil mist. Replacement is 59% muff and 50% gearbox.
United Airlines	214	Utilizing a muff and "O" ring grease seal on generator—in service short time.

It is evident from the above information that the muff is being used for almost all types of engine accessories.

Information from the Kingsville NAS and the Jacksonville and Alameda NAVAIREWORKFAC(s) indicated that in the case of the Lycoming CSD, an earlier design used a muff which apparently was not

very effective and has been substituted by a one-piece dogbone spline. The one-piece dogbone spline has also not been effective (Survey Form Nos. 170 and 207) in reducing spline wear on the CSD interface splines. Lycoming is recommending (Appendix E, Item 6e) the use of essentially the same design as the earlier muff design.

Quonset Point engineers report that the muff splines will be used on most new designs, either dry or wet pad (see Appendix E, Item 8i). It is believed that the muff spline can indeed be of significant value to the spline connection since it will permit the spline connection to accept more misalignment and could perhaps be designed as an expendable member between the accessory and the gearbox. No reports have been obtained from the NATC regarding any evaluations relating to the spline muff, as has been the case for the proposed "wet pad" design. In any case, the muff should be designed with the ultimate aim of protecting the female spline at the gearbox. Although the muff spline is widely used, it is believed that it has not been designed as a sacrificial member to protect the female spline on the gearbox.

8. Oil Mist

The oil mist (sometimes referred to as mist or oil spray) lubrication method used on some engine accessory gearbox applications was discussed in Chapter VII. Information obtained from some sources is indicated below:

Facility	Remarks
Alameda	Proposed for T-56 alternator and hydraulic pump, see Appendix E, Item 13d.
Alameda	Provide for J-65 fuel pump and hydraulic pump, see Appendix E, Item 6b.
Alameda	Provide for J-65 magneto generator and fuel control, see Appendix E, Item 6g.

9. Plating Repair

Splines which are allowed to wear only a small amount can usually be repaired by plating. Spline connections having relatively short lives and consequently high replacement rates may not be capable of accepting a plating repair.

The following facilities are currently utilizing plating repair:

Facility	Survey Form No.	Remarks
Jacksonville	171	Chrome flash NAVAIR 03-110DAA-17
Jacksonville	173	Chrome flash
United Airlines	215	Machine off spline taper and plate
United Airlines	216	Chrome flash male and female spline

United Airlines engineers reported (Survey Form No. 215) that at approximately 8000 hours, excessive spline wear is encountered within the engine on the front rear hub. The splines exhibit tapered tooth wear. The excess taper is machined off and the spline is plated with a hard nickel coating followed by a chrome flash. Most hubs have a retirement life of 16,000 hours at which time the hub is discarded.

Personnel at the Alameda Materials Laboratory have been developing the use of selective plating for rebuilding landing gear struts since 1964. The technique has not been used for rebuilding worn splines, however, the process could be feasible if the cost is not prohibitive when compared to that of a new part.

10. Redesign

In a number of cases, some redesign of the spline connection has been performed in an effort to minimize spline wear. Some of the redesigns reported refer to the adoption of a grease retention method.

Facility	Survey Form No.	Action	Remarks
Cherry Point	224	Current	Entire fuel control is being replaced with a new design.
Pensacola	122	Current	LED NA03-5CA-52/PN4 specifies pin measurement and replacement of dogbone spline.
Quonset Point	187	Proposed	Lengthen the male spline and incorporate an "O" ring on male spline.

Facility	Survey Form No.	Action	Remarks
Kelly	96	Current	Redesign shaft for "O" ring; T. O. 8A-10-2-502, Nov. 1963.
Tinker	197	Proposed	Lengthen male spline if misalignment is not excessive.
AiResearch	160	Current	Replacing long shaft with shorter one to minimize orbiting of spline connection.

11. Research Program

Problems with excessive spline wear on an AiResearch high-pressure fuel pump (Survey Form Nos. 161 and 218) for splines operating in a fuel environment have been under study at SwRI under Navy sponsorship. An abstract of this work is included in Appendix A. In this work, various spline materials and surface treatments were evaluated. Tests performed at a misalignment of 0.006-inch/inch of spline length for 1000 hours in JP-5 produced total spline wear of 0.0013 inch. The spline connection consisted of a crowned male spline of M-50 steel with a heat-treated Electroless Nickel II coating, operating against an uncoated uncrowned AISI 4130 female spline.

12. Seals

Seals in the form of "O" rings and boots are being used to prevent contamination and to retain lubricant in several applications. It was reported that centrifugal force can cause the grease to move away from the spline connection thereby decreasing the life of the connection. Information relative to seals was collected on the survey forms and is listed below:

Facility	Survey Form No.	Action	Remarks
Quonset Point	187	Proposed	Incorporate an "O" ring on male spline.
Kelly AFB	96	Current	Incorporate an "O" ring on male spline.

Facility	Survey Form No.	Action	Remarks
United Airlines	214	Current	Incorporate an "O" ring and muff; in service for only 4 months—beneficial effects unknown.
American Airlines	201	Current	"Trouble-free installation". Incorporates a boot seal, uses Molykote 343X grease, and a muff.

13. Surface Treatment

Several types of surface treatments in the form of coatings and films are under study by various facilities. Information collected on the survey forms regarding surface treatments is listed below:

Facility	Survey Form No.	Action	Remarks
Alameda	210	Current	"Trouble-free installation". Utilizes Microseal 100-1 on spline; applied once, see Appendix E, Item 13b. Allison proposed wet pad, see Appendix E, Item 13a.
Kelly AFB	99	Proposed	Test stand evaluation of Nylon-coated male spline, see Appendix E, Item 9a.
ARADMAC	137	Proposed	Contemplating hard coating on wear surfaces.
ARADMAC	142	Proposed	Possible corrosion and wear resistant coating on mating spline.
ARADMAC	144	Proposed	Better wear surfaces on both splines.
AiResearch	161, 218	Current	Several metallic coatings have been investigated for fuel environment (see Appendix A). Splines with Electroless Nickel II coating now under test at AiResearch.

14. Wet Pad

The wet pad lubrication method has been described in Chapter VII. The consensus of American Airlines, United Airlines, Lockheed, Boeing, and Sundstrand is that the wet pad design is the only effective manner by which excessive spline wear can be eliminated at the engine accessory gearbox. However, for existing aircraft, the conversion of a dry pad to a wet pad is costly, and effective maintenance has also been questioned by some.

a. Conversion to Wet Pad

The use of wet pad in place of dry pad has been carried out in one application and proposed in several others, as shown below:

Facility	Survey Form No.	Remarks
Alameda	209	Allison is proposing a wet pad for starter-gearbox on T-56 engine, see Appendix E, Items 13c and 13f.
Alameda	210	Allison is proposing a wet pad for alternator-gearbox on T-56 engine, see Appendix E, Item 13a.
Norfolk	176	Allison proposed wet pad on alternator-gearbox.
North Island	227	"Trouble-free installation". Problem solved by incorporating a wet pad on the fuel pump, see Appendix E, Item 5c.
Tinker	194	Proposed for CSD on TF33-P9/-P3.
Tinker and Navy	196, 198	Tinker proposed for CSD internal splines on J-79 engine, see Appendix E, Items 8a, 8b, 8c, 8d, and 8f for NATC evaluation.

b. Wet Pad on J-65 Engine Gearbox Using 8-Tooth Splines

Quonset Point engineer's reported that the interface spline connections on the J-65 engine gearbox to various accessories had been an area of severe spline wear. To reduce the excessive spline wear, Curtis-Wright proposed an 8-tooth spline for all of the interface spline connections and the wet pad design. The components involved are Pesco fuel pump, TRW fuel pump, Bendix Magneto-generator, and front and rear hydraulic pumps. It has been reported that the modification has been made in accordance with powerplant changes (see Appendix E, Items 6i, 6j, 6k, and 6l). Information obtained from Alameda indicates that the usage rate on the mating spline connections is now less than 15 percent. Quonset Point reports that the change is very effective.

c. Wet Pads for New Aircraft

Information obtained in this survey has revealed many new aircraft engines will have wet pads as illustrated in Table 25.

TABLE 25. WET PAD LUBRICATION FOR VARIOUS MILITARY AND COMMERCIAL AIRCRAFT

Aircraft	Engine	Engine Manufacturer	Components Involved	Source
Military				
B-52H (Air Force)	TF-33	P&W	CSD 120AGD04	Sundstrand design field tested (Survey Form No. 195)
C-5A (Air Force)	TF-39	GE	CSD, generator	Sundstrand representative at Jacksonville NAVAIREWORKFAC
F-4B (Navy)	J-79	GE	CSD 30AGD03	Sundstrand; wet pad approved
RA-5C (Navy)	TF-33	P&W	CSD 40AGD01	Sundstrand; Navy flight testing wet pad
S-3A (Navy)	TF-34	GE	Generator, starter, hydraulic pump, CSD, fuel pump	Lockheed, GE representative
Commercial				
DC-8-10	JT-3D	P&W	Generator, starter, hydraulic pump, CSD, fuel pump	UAL, Boeing
DC-8-60	Unknown	P&W	CSD 60AGD12	Sundstrand
DC-9	JT-8D	P&W	CSD 60AGD04	Sundstrand
DC-10	JT-9D	P&W	CSD 90AGD01	Sundstrand
DC-10	CF6-6	GE	Generator, starter, hydraulic pump, CSD, fuel pump	UAL, Boeing
F-28	Sprey	RR	CSD 20AGD02	Sundstrand
747	JT-9D	P&W	Generator, starter, hydraulic pump, CSD, fuel pump	UAL, Boeing
SST	GE-4	GE	All accessories	Sundstrand

X. RECOMMENDED IMPROVEMENT PROGRAMS (REWORK AREA)

A variety of techniques may be employed or considered in order to improve spline reliability, extend spline life, and reduce overall spline maintenance cost. These techniques fall generally under two categories: those that represent state of the art and thus may be immediately put into effect on existing equipment without requiring further study, and those that are deemed particularly promising but cannot be put into effect without further work to iron out the technical details. For the sake of convenience, techniques of the former category are herein termed "improvement programs" and will be discussed in this chapter, while techniques of the latter category are herein termed "technology gaps" and will be discussed in the next chapter.

In general, the immediate improvement programs recommended herein have been backed up by convincing service or research and development experience; indeed most such techniques have been used to some degree in practice though not on a service-wide basis. Moreover, as they can be readily introduced to existing equipment without design alterations, so by their very nature they all belong to the rework area. In other words, they can be immediately introduced to the Navy's rework program.

These immediate improvement programs are of particular value to the interface splines which are by far the most troublesome in practice. However, most such techniques are also applicable to the other classes of splines (i.e., those located inside the engine or gearbox envelope and those located in the airframe) which generally experience only minimal to moderate difficulties.

In the interests of reduced maintenance, increased reliability, and extended life, it is recommended that the Naval Air Systems Command consider the immediate introduction of the following improvement programs in the Navy's rework cycle:

1. Spline Misalignment Control

The survey has revealed that little emphasis has been given to controlling spline misalignment between the mating spline parts, although the importance of misalignment control is widely recognized. It should be emphasized that the misalignment of real significance is that between the assembled male and female splines after the two components to which they are attached are actually assembled.

As commented in Chapter VI, the AND and MS design standards are deficient in various respects, including the specifications on alignment tolerances. In essence, these standards prescribe the tolerances on the alignment of each individual spline part in relation to the component to which it is attached, and also prescribe the tolerances of each individual component mounting device—so that if all these tolerances are met, the assembled spline-to-spline alignment is automatically assumed to be acceptable when the two components are put together. This seemingly logical procedure has two drawbacks. First, the existing alignment specifications are inadequate and do not assure the best possible spline-to-spline alignment when the stackup errors in the complete spline connection that result from assembling frequently interchangeable components are taken into account. Second, their allowable lateral misalignment is in excess of the minimum chordal clearance so that mechanical interference can result. Possible revisions of the design standards fall under the category of technology gaps to be discussed in the next chapter. Nevertheless, the deficiency of the current design standards in this and other respects should be kept in perspective.

In practice, misalignment control even to the extent provided for in the design standards is difficult to carry out, due to a lack of suitable technique to measure the lateral as well as angular misalignments between the spline part and the component to which it is attached. This critical task is now left largely to the ingenuity of the maintenance personnel. The matter is further complicated by the fact that different components are serviced by different groups without adequate liaison between them, so that there is in effect little real spline-to-spline misalignment control due to divided responsibilities.

The problem was recognized midway during the course of this study, and a recommendation to alleviate it was submitted to NASC on January 29, 1971 for consideration and possible implementation (see Recommendation No. 1, Appendix F, for details). Key items in this recommendation are as follows:

a. Until the design standards are revised and updated, conformance of the spline-to-component alignments, both lateral and angular, should be checked and assured.

b. A uniform method of measuring the lateral and angular spline-to-component alignments should be established. An example of such a measuring technique was suggested.

c. These measurements should be initially confined to those spline connections identified by the NAVAIREWORKFAC(s) to have experienced particular difficulties, with consideration to expand the program when real benefits are established on an overall cost effectiveness basis.

2. Improved Liaison between Organizations

Spline replacement rate is affected by many factors, including misalignment between the mating splines, lubricant, lubricating method and frequency, material combinations, overhaul and inspection practices, and spline wear rejection criteria. This survey indicated that control over these factors is exercised generally by several different groups, with no one group solely responsible for the complete spline connection.

This problem was also recognized midway during the course of this study, and a recommendation to alleviate it was submitted to NASC on January 28, 1971 for consideration and possible implementation (see Recommendation No. 2, Appendix F, for details). Key items in this recommendation are as follows:

a. Improved liaison should be established between groups responsible for interface splines to effect better control over all factors affecting spline wear and to prevent individual groups from taking actions which might result in increased overall spline maintenance costs.

b. In the event significant improved liaison cannot be obtained, it may be desirable to create an organization with the specific responsibility for the complete interface spline connections.

3. Lubrication of Three Upper Splines on Main Rotor Mast of UH-1 Series Helicopters

As explained in Chapter V, the three upper splines on the main rotor mast of the UH-1 series helicopters experience a severe pitting problem. It was ascertained that this problem was caused, at least in part, by improper lubrication. Apart from possible redesign or development, it was felt that improved lubrication could help considerably.

This problem was also identified midway during the course of this study, and a recommendation to alleviate it was submitted to NASC on January 28, 1971 for consideration and possible implementation (see Recommendation No. 3, Appendix F, for details). Key items in this recommendation are as follows:

a. The three problem splines should all be lubricated with an appropriate grease during overhaul, and relubricated thereafter at 100-hr intervals.

b. Neither the MIL-C-11796 corrosion-preventive compound nor the MIL-G-25537 grease, which are currently used, is a good spline lubricant. Their use should be discontinued.

c. In place of the above, use of a MIL-G-21164 grease for service temperatures up to 250°F and a MIL-G-81322 grease for service temperatures up to 350°F is recommended.

4. Grease Selection

As explained in Chapter VII, there is such a proliferation of greases now used for interface splines, apparently with no systematic control on a service-wide basis, that proper or optimum lubrication cannot be assured. Tables 18 and 19 show that the greases come under a variety of military specifications, federal stock numbers, and brand names—to such an extent that appropriate systematization and standardization are urgently needed. In addition, there is a desire on the part of many people interviewed for better greases than those currently available, which can potentially further complicate an already baffling situation. Systematization and standardization of current greases and development of new greases belong to the realm of technology gaps to be discussed in the next chapter. In the meantime, an interim list of a few allowable current greases will not only simplify the inventory system; but also enhance lubrication, improve performance, and increase overall cost effectiveness.

The following recommendations, made with the above objectives in mind, are presented for NASC to consider and possibly adopt:

a. The MIL-G-3545, MIL-G-7187, and MIL-G-7711 specifications are now obsolete. Greases supplied under these specifications should be withdrawn from the inventory system and not used in maintenance operations.

b. Pending systematic evaluation and possible issuance of appropriate additional specifications, the use of other greases should be discouraged.

c. In the interim, it is recommended that the MIL-G-21164 greases be used for service temperatures up to 250°F and the MIL-G-81322 greases be used for service temperatures up to 350°F, for interface splines on a service-wide basis.

5. More Frequent Relubrication

From the information gained in this survey, interface splines are normally lubricated during initial installation and during engine or

accessory overhauls which vary from 400 to 3000 hours, with an approximate average of 1250 hours. These splines are relubricated in service at intervals ranging from 60 to 1500 hours, with an approximate average of 640 hours. In critical applications where the splines are overloaded either due to inadequate design or presence of excessive misalignment due to dynamic conditions, or due simply to inadequate misalignment control, the burden to be assumed by lubrication becomes all the more severe largely by default. As pointed out in Chapter II or Appendix A, a good grease (such as MIL-G-21164 and MIL-G-81322) has a long induction period which is chemical in nature, and frequent renewal of the grease will provide continued negligible wear. Moreover, the grease may be lost through inadequate sealing, which also demand more frequent replenishment. More frequent relubrication obviously increases the maintenance cost and increases the equipment down time, and should not be practised indiscriminately. Nevertheless, it does improve overall reliability and spline life, which are equally, if not more, important.

In view of the above considerations, it is recommended that NASC consider and possibly adopt the following relubrication practice:

a. Pending review of the other factors recommended in this chapter, the relubrication interval for interface splines which experience excessive wear should be shortened by 50 percent, or to 25 hours of flight time in the most critical cases.

b. As all of the improvement programs recommended in this chapter are put into effect, the matter should be reviewed at the NAVAIREWORKFAC level and the relubrication interval may be progressively lengthened as the service records so indicate.

6. More Thorough Cleaning

Particular attention should be given to cleaning both the male and female splines prior to relubrication, which is normally carried out at the squadron level under rather trying circumstances. Additionally, even at the NAVAIREWORKFAC level during overhauls, the task is not as easy to accomplish as it would seem. By virtue of the design, the female spline is usually the longer one and cannot be removed from the component to which it is attached except in the case of a complete teardown, so it is far less accessible than the male spline for thorough cleaning. It is believed that this problem can be alleviated with foresight in design. Nevertheless, for current equipment, the merits of thorough cleaning cannot be overlooked.

The recommendations for NASC to consider and possibly implement are as follows:

a. During overhauls and relubrication, the importance of thorough cleaning of both the male and female splines should be emphasized.

b. To aid in the cleaning of the female splines, suitable cleaning brushes, shaped like small tooth brushes with stiff stainless steel "bristles", should be provided the maintenance personnel. These brushes should be thoroughly cleaned with solvent, or else discarded, as the condition dictates.

7. Reverse Splines in Gearbox

Some manufacturers utilize several gear-spline shafts within the accessory engine gearboxes or helicopter combining gearboxes. In some instances, as in the case of the combining gearbox on the H-3 helicopter, there are two relatively massive identical gear-spline shafts. Since the identical shafts are gear-connected and operate in opposite directions, it would be possible to interchange the shafts thereby providing new spline and gear surfaces and effectively doubling the life of each shaft.

It is therefore recommended that NASC consider and possibly permit the following rework procedure:

a. The gearbox inventory should be reviewed at the NAVAIREWORKFAC level to determine where identical gear-spline shafts are used.

b. Those gear-spline shafts worn only on one side should be carefully inspected. If found usable on the unworn side, they should be carefully cleaned and preserved, and be permitted to be used in the reversed service.

8. Muff

As discussed in Chapter IX, the spline muff has been employed in practice and has received many favorable reports. The muff is normally supplied as a part of the accessory, consequently its design is governed by the accessory manufacturer and the appropriate design standard. Its primary purpose is to permit the connection to accept some misalignment and thereby minimize spline wear—particularly that on the difficult-to-replace female spline. Although the concept of spline muff can be exploited to the extent of developing an "expendable bolt-on spline" or an "expendable muff" (see the next chapter concerned with technology gaps),

the use of muffs as presently available is deemed helpful if not necessarily the best possible.

In view of the foregoing, it is recommended that NASC consider and possibly endorse the following practice:

a. In those cases where excessive spline wear is experienced, the use of a spline muff should be accepted.

b. Proliferation of state-of-the-art muffs should be discouraged, pending a thorough review of the other improvement programs recommended in this chapter and an evaluation of improved muff designs.

XI. TECHNOLOGY GAPS

The "improvement programs" recommended in the preceding chapter represent techniques that can readily be employed on existing equipment without calling for design changes. They are, by their very nature, state-of-the-art measures whose implementation should help substantially to alleviate the spline failure problem, particularly as related to the interface splines.

The gravity of the spline failure problem demands, however, that further improvements be made at the design stage or beyond the state of the art. Since these measures will require changes in design concept or further research and development, they are termed "technology gaps."

The present chapter will identify the technology gaps which, for the sake of convenience, will be dealt with under two headings, namely, those that belong to the rework area and those that belong to the area of research and development.

A. Rework Area

The technology gaps in the rework area are those which relate to improved rework techniques. When developed, these techniques can readily be applied equally to current and future equipment. The need for these measures is obvious from the survey conducted, and it is recommended that the Naval Air Systems Command consider their development at an early date.

1. Misalignment Measurement

It was mentioned in the preceding chapter that the misalignment of real significance is that between the two mating spline parts when the components to which these spline parts are attached are assembled. The importance of misalignment control has been repeatedly emphasized in this report and is generally recognized by all rework personnel. However, obviously, spline-to-spline misalignment cannot be effectively controlled unless it can be accurately measured in the first place.

In the preceding chapter, a method of measuring the spline-to-component misalignment was suggested. It is implied that if the spline-to-component misalignments for the two components to be joined together are within some prescribed limits, then when the two components are actually assembled the resulting spline-to-spline misalignment will be acceptable. The method suggested in the preceding chapter is one of

several that can be conceived, and it has indeed been used in practice to some extent. But the method is rather complex and cannot easily be used at the squadron level. There is a need for a technique which can more easily be employed by the squadrons where most of the routine accessory replacements are made.

In addition to a technique described, there is a need for the direct measurement of the spline-to-spline misalignment. Such a technique is required because of stackup errors of parts, so that the very best of spline-to-spline alignment cannot be assured by the current design specifications. Even in the long run, i.e., after better design standards have been developed, there is still a need for direct spline-to-spline misalignment control for splines in critical applications or locations. As emphasized in the earlier chapters, good alignment eases the role of maintenance greatly and cannot but save maintenance cost in the long run.

Summarizing, it is recommended that NASC consider the development of the following techniques:

a. A technique for measuring spline-to-component misalignment that is simple to use and suitable to the needs of the squadrons.

b. A technique for measuring spline-to-spline misalignment for splines in critical applications or locations, suitable for use at all levels of maintenance.

2. <u>Misalignment Control</u>

Misalignment control cannot be exercised without misalignment measurement and without adequate provisions in the design. The matter of design is not assumed to be a rework function. Thus, in practice, all that the rework personnel can do is to accept or reject splines that do not provide acceptable alignment.

There are currently no quantitative information on the effect of lateral and angular misalignments on spline wear. Information of this type is needed in order to specify acceptable limits.

It is recommended that NASC consider the development of the following information:

a. Quantitative information on the effect of controlled lateral and angular spline-to-spline misalignments on spline wear.

b. Development of allowable misalignment tolerances for use in the rework sequence.

3. Wear Measurement

The purpose of misalignment control is to prevent excessive spline wear. The purpose of wear measurement is to measure the extent of wear that actually occurs, so as to form the basis of spline replacement.

As related in Chapter VIII, a large number of tools, gages, or instruments are currently being used to measure spline wear. Some of these are simple to use, and some are quite elaborate. The variety is such that there is at present no common basis for comparison. Standardization of a few techniques to be used service-wide will help to eliminate confusion, enhance quality control, and bring about lower overall maintenance cost.

The matter will require careful study; but some guidelines are apparent. Some simple tools are needed for squadron use. By their very nature, these tools may not be applicable to critical splines which can only tolerate very little wear. At higher levels of maintenance, more sophisticated tools are justified, and several of these are indicated in Table 22. The rather popular use of visual inspection reflects probably the acute recognition of the importance of wear on spline performance. While it is not an "objective" technique, it can well be a useful complement to the instrumental techniques and thus need not be discouraged at this time. As progress is made on the instrumental side, less reliance will automatically be placed on the visual inspection.

The Versa-dial gage with Q. P. tips has been reported to give good results. But they are expensive and their use is likely to be limited to the depot level.

A technique which is most popularly used is the pin or wire method; or its variation, the ball method, which is apparently not widely used. Tools of this category are easy to use and quite inexpensive, and they are inherently suitable for all levels of maintenance. Their principal drawbacks are, as discussed in Chapter VIII, their inaccuracy due to involute profile changes due to wear and, in the case of pins or wires, some other complications. Nevertheless, their low cost and their adaptability to all levels of maintenance, after these problems are resolved, offer attractive possibilities.

It is therefore recommended that NASC consider the implementation of the following in the area of spline wear measurement:

a. Development of the pin or ball technique taking consideration of tooth profile changes due to wear and other complications.

b. Standardization of a few spline wear measurement techniques, with due recognition of the needs at different levels of maintenance.

4. Rejection Criteria

Spline rejection involves considerations of overall performance, reliability, and cost. Indiscriminate rejection of usable splines increases maintenance cost; indiscriminate acceptance of nonusable splines impairs performance and reliability. It is difficult to strike a happy compromise, because the compromise obviously depends on the application. In many instances, all that is required of a spline connection is to drive an accessory and no other factors need to be taken into consideration. Even so, the spline that passes the inspection during one overhaul must be able to survive till the next overhaul in order to ensure operational reliability. In this regard, passing of those splines that have worn close to the case depth appears to be false economy.

On the other hand, there are applications where other performance indices should also be considered. For example, on constant speed drives, noise and vibrations may be important. In such applications, more stringent rejection criteria are required.

Table 23 shows that there are, at present, a variety of spline rejection criteria, ranging from a few thousandths of an inch (usually specified quantitatively in each application) all the way to "knife edge", or even "individual discretion" or "not specified". The latter two criteria are too vague to be meaningful.

It is therefore recommended that NASC consider the development of the following spline rejection criteria:

a. The "individual discretion" and "not specified" criteria should be made quantitative.

b. The "few thousandths of an inch" criteria should be reviewed and consolidated.

c. The other spline rejection criteria should be consolidated and set in such a way as to assure reliable operation to the next overhaul. With case hardened splines, the criterion should realistically

be related to the case thickness (and the current design standards are deficient in this respect, see Chapter VI). With through hardened splines, a more liberal criterion may be considered.

B. Research and Development Area

The research and development efforts to be outlined herein are generally related to design, materials, and lubricants. Fundamentally, the technology gaps in the rework area just presented deal with maintenance techniques, and they are applicable to both current and future equipment. The research and development programs are directed toward the future; their dividends in the long run lie in better performance, increased reliability, longer life, and—not the least—reduced maintenance.

The following research and development programs are presented to the Naval Air Systems Command for consideration and possible implementation:

1. Design Standards

As discussed in Chapter VI, a number of design standards are currently available; but the pertinent ones to aircraft splines are basically the AND and MS standards. It is gathered that the MS standards are intended to supersede the AND standards. Nevertheless, even though the MS standards represent many improvements over the AND standards, they also contain provisions that appear to make backward strides (such as the lack of a case thickness specification, and the specification of a minimum case hardness only for the male spline which is the more easily replaced part). In any case, as summarized in Table 17, both standards are either inadequate or require further study in every relevant respect.

It is not necessary to repeat here the comments already made in Chapter VI. All that needs to be emphasized is that the decisions made at the design stage affect virtually all aspects of performance, reliability, maintenance, and overall operating cost. There is hardly any question that a new set of design standards should be developed. Such a development program will require much time and considerable study and coordination, thus its initiation should not be delayed. The problem is fundamental.

In view of the above, and recognizing the time and effort required to develop a set of new design standards, it is recommended that NASC consider the following:

a. Allow the interim use of the MS standards but incorporate into them the case thickness and case hardness provisions of the AND standards, prior to the adoption of a new set of design standards.

b. Initiate a program to develop a new set of design standards, taking all factors listed in Table 17 into consideration.

2. Materials

Table 13 lists a large number of materials currently used for splines, though the majority of the splines are made of AMS 6260 (AISI 9310) and AMS 6415 (AISI 4340) steels. These are two "workhorses" of long standing, with AMS 6260 exhibiting better wear resistance (see, for example, Appendix A). AISI M50 steel is not widely used on interface splines; but shows good results when used with Electroless Nickel II coating in a fuel environment (Appendix A). In addition, there are other materials that may be considered.

In general, apart from AMS 6260 and AMS 6415 steels, there is not enough background information to formulate sound design decisions. The missing information needs to be developed by systematic evaluation. So far as AMS 6260 and AMS 6415 are concerned, AMS 6260 is more wear resistant and should be favored for female splines which are difficult to replace, while AMS 6415 is less wear resistant and should be favored for male splines. As shown in Table 13, this is indeed the overall choice in practice.

In view of the above, it is recommended that NASC consider the following:

a. Encourage the use of AMS 6260 steel for female splines and AMS 6415 steel for male splines.

b. Initiate a systematic program to evaluate other promising materials for future applications.

3. Coatings

The fact that coatings can greatly enhance spline wear life has been amply demonstrated (see Appendix A). What is not presently clear is the optimum type and thickness of the coatings. There are two broad types of coatings: plastic and metallic.

As reported in Appendix A, a plastic coating, Nylon-11, gave very long wear life for a generator spline application when used with oil mist lubrication. On the other hand, the same coating, when applied by what was believed to be an inferior technique, yielded only modest performance in a fuel environment. Whether the excellent results obtained on the generator spline was due to the superior coating application technique, or the superior lubricating quality of the lubricant as compared

with a fuel, is not known. In any case, the information now available is most encouraging. Besides, plastic coatings do have the advantage of minimizing vibrations—a characteristic important in many applications. Thus, the plastic coatings definitely merit attention.

Appendix A also shows that several metallic coatings gave excellent wear life in a fuel envoronment, the best being Electroless Nickel II. This coating was applied to a male spline of M50 substrate, and was used with a female spline made of AMS 6415 (AISI 4130) steel. For usual interface spline connections, it would appear desirable to provide for a longer wear life for the female spline which is difficult to replace. It would thus appear to be desirable to apply the Electroless Nickel II coating on the female spline. With the life thus gained on the female spline, perhaps a different material, such as AMS 6260 steel, might be considered for the male spline. However, the compatibility of the nickel coating versus AMS 6260 has not been evaluated. Clearly, optimum use of metallic coating, particularly with grease in air environment, which represents the bulk of interface spline application, deserves further investigation.

Summarizing, it is recommended that NASC consider the following evaluation programs:

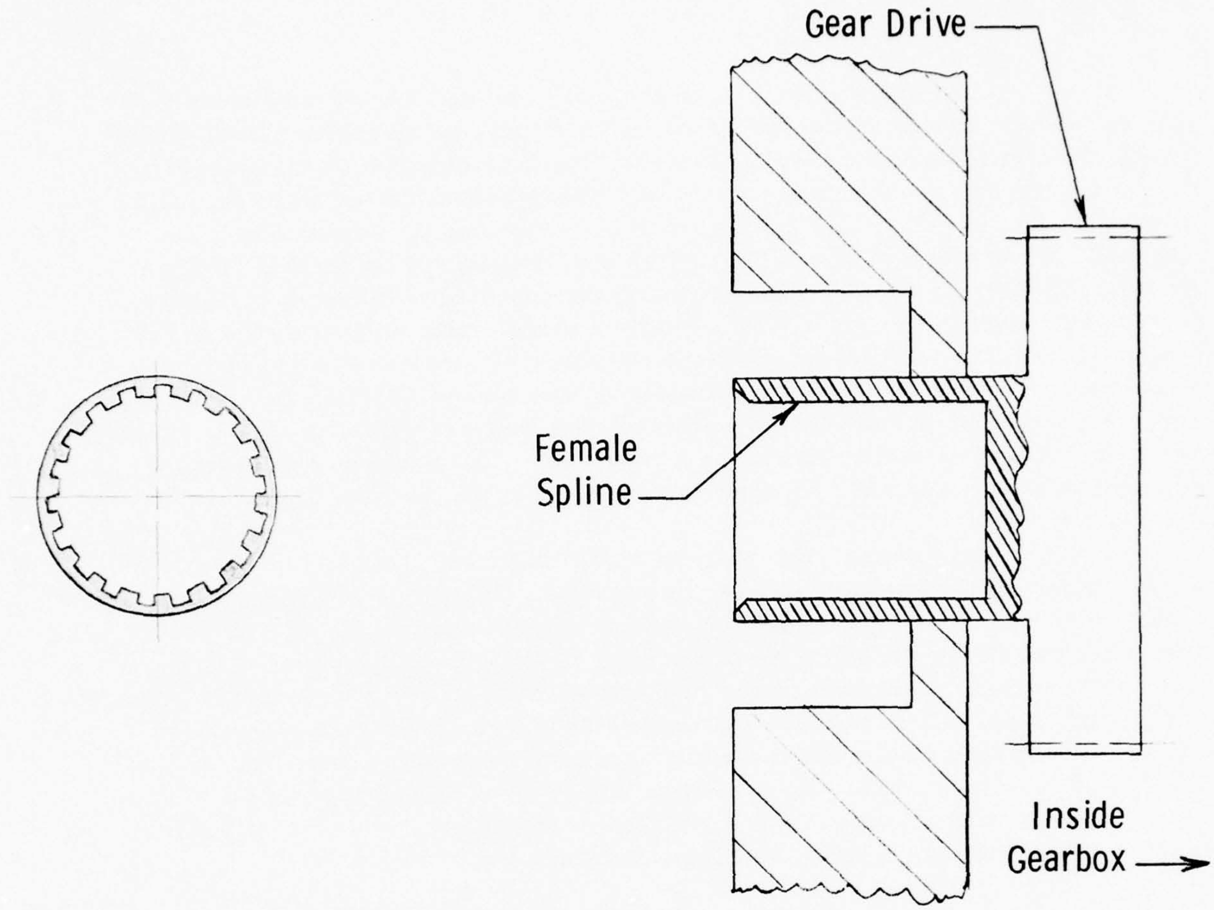
a. Systematic evaluation of selected plastic coatings, such as Nylon-11, in air, fuel, and lubricant environments for spline use.

b. Systematic evaluation of metallic coatings, such as Electroless Nickel II, in air, fuel, and lubricant environments for spline use.

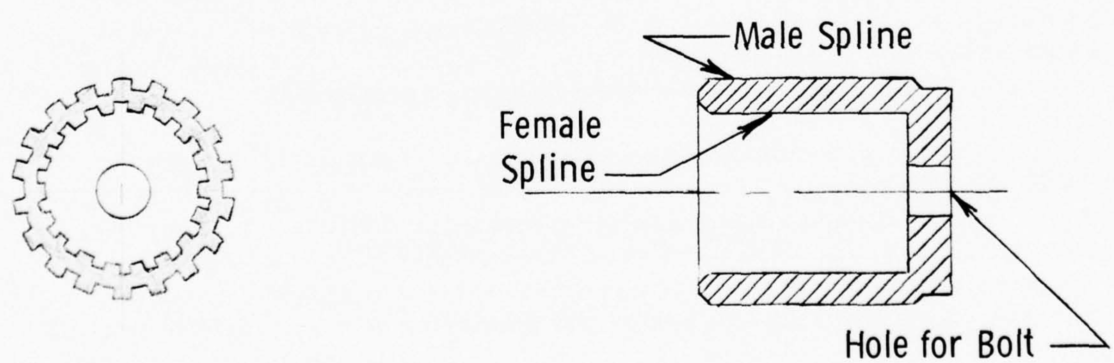
4. Expendable Bolt-On Spline

The expendable bolt-on spline is one of several techniques, all of which may be considered as an extention of the spline muff concept discussed in the preceding chapter. It is believed to be worthy of exploitation from the economic standpoint.

Figure 10A illustrates a conventional engine accessory gearbox pad spline connection. In this design, several female splines are provided on the gearbox to drive various engine accessories. An accessory, such as a generator, fuel pump, hydraulic pump, or starter, will have a male spline which mates with a corresponding female spline on the gearbox. In this arrangement, once the female spline is worn, it must be replaced; but that would entail dissembly of the gearbox.



A. TYPICAL GEARBOX



B. EXPENDABLE BOLT-ON SPLINE

FIGURE 10. TYPICAL ENGINE ACCESSORY GEARBOX AND BOLT-ON SPLINE

This problem can be overcome by the use of a bolt-on spline, which is illustrated in Figure 10B and may be described as a blind muff. The bolt-on spline will have a male spline capable of mating with the female spline on the gearbox. The female spline on the bolt-on spline is sized to accept the male spline on the corresponding accessory. A bolt hole is provided at the blind end of the bolt-on spline so that it can be secured to the female spline on the gearbox. Since there is virtually no motion between the male bolt-on spline and female spline on the gearbox, this results in eliminating the possibility of wear at the gearbox female spline. As a result, the female spline on the gearbox never needs replacement. When the female spline on the bolt-on spline is worn, it can easily be removed and replaced by a new one. The male spline on the accessory can, as usual, be readily replaced in the rework process.

In a sense, the bolt-on spline is not a completely new concept, except in the manner it is to be applied. A type of bolt-on spline connection was found to be used on the Bendix automatic-disengaging gear type starters (Fig. 4). The main purpose of this type of bolt-on design was to disengage nearly all of the rotational mass of the starter once the engine has started. A similar concept is also used on the JT-8D engine. Figure 11 illustrates the kidney-shaped engine accessory gearbox used on the JT-8D engine and the two locations where the bolt-on type splines are used, namely, on the starter and the CSD. However, no additional information was obtained relating to these connections.

Tinker engineers reported that a type of bolt-on spline is used on a CSD-gearbox on a TF-33-P9 engine used on the EC/RC/135C and B-52H aircraft (Survey Form No. 195). In this case, a bolt-on dogbone type spline was used. The dogbone spline was bolted into the gearbox thereby saving the gearbox spline. In this problem area, it was reported that the female spline on the dogbone had a replacement rate of 12% while the mating CSD male spline had 17% replacement rate. The bolt-on spline can be removed once the CSD is removed without disturbing the gearbox.

A bolt-on dogbone type spline is also used in a J-85 engine for a T-38 aircraft (Survey Form No. 99), as reported by Kelly. In this case the dogbone spline is bolted into the generator, obviously to save the generator spline. In the sample worn splines obtained from Kelly, the end of the dogbone spline mating with the gearbox was worn to a knife-edge, while the other end which was bolted to the generator was virtually in perfect condition.

In the interests of saving maintenance cost, it is recommended that NASC consider the following:

a. Development of expendable bolt-on splines of optimum design for use in critical interface spline connections.

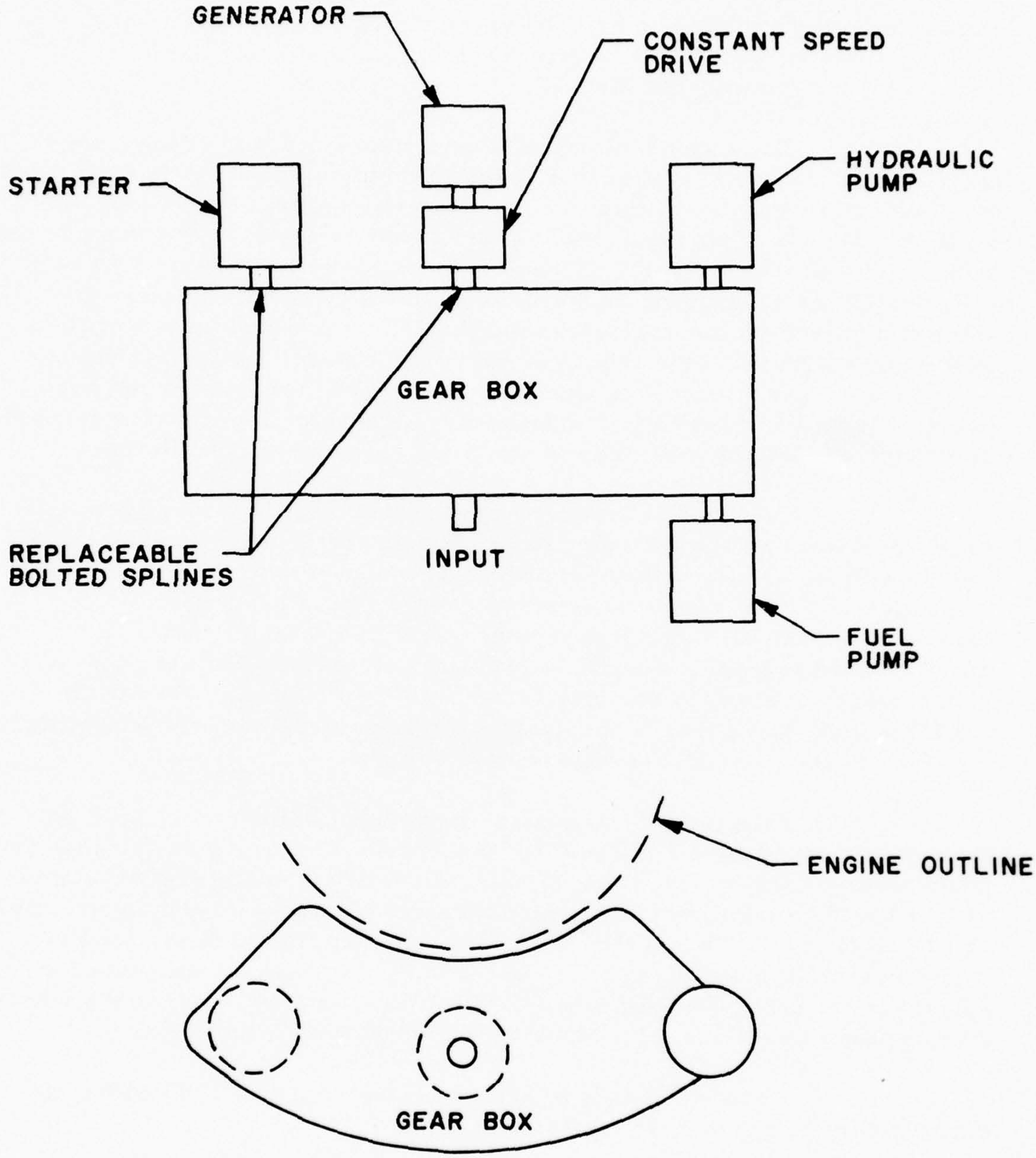


FIGURE 11. SPLINE CONNECTIONS ON GEARBOX OF JT-8D COMMERCIAL AIRCRAFT ENGINE

b. Modification of existing gearboxes to accept expendable bolt-on splines in critical applications.

5. Expendable Muff

The expendable muff is an extension of the conventional muff concept in another direction. The conventional muff is incorporated to allow the spline connection to accept misalignment. It is worthwhile as such. On the other hand, as long as a muff is employed, and since the muff can be easily replaced, it would appear sensible to design the muff deliberately as an expendable item, in such a way as to minimize the wear and therefore the replacement of both the male and female splines which mate with it. This technique may well protect the female splines on the engine gearboxes long enough to last through the scheduled overhauls. Further, it may save unnecessary rework of accessories rendered unserviceable only due to wear of the male splines attached to them.

One way to design an expendable muff is to design it as a sacrificial item as suggested. Under this concept, the mating male and female splines should both be deliberately made to suffer minimum wear by proper choice of material, coating, and/or case hardness. The sacrificial muff will then be designed, again by choice of material, coating, and/or case hardness, to be the sacrificial element. To carry this concept further, it appears entirely feasible to employ materials for the expendable muff that possess lubricating quality, thereby further lengthening the lives of the mating male and female splines.

Another way to design an expendable muff is to build an energy-absorbing capability into it. An energy-absorbing muff, when interposed between the mating male and female splines, will reduce the true slip at its internal and external interfaces, regardless of the apparent slip or misalignment. This technique will then accept more misalignment without actually entailing much relative motion or wear. Its secondary advantage is that it will also absorb vibrational energy, so that the vibration problem in some applications can be effectively minimized.

Accordingly, it is recommended that NASC consider the development of expendable muffs as follows:

a. Development of an expendable muff of the sacrificial type.

b. Development of an expendable muff of the energy-absorbing type.

c. Evaluation of the comparative merits of the expendable bolt-on spline, sacrificial muff, and energy-absorbing muff, with a view toward standardization.

d. Modification of existing equipment to incorporate the best design.

e. Incorporation of the best design in future equipment.

6. Lubricants

Three general classes of lubricants were considered in Chapter VII and further commented on in the preceding chapter. Of these three classes, the liquid lubricants give generally satisfactory performance; but they cannot be incriminately used in interface splines due to consideration of system complexity and weight and size. Greases are employed in most interface splines; but there are problems—most of which may not be related to the grease itself, but rather due to inadequate design, installation, and maintenance. Solid-film lubricants provide little protection to splines.

One of the problems with greases is the great proliferation of greases currently used, as discussed in the preceding chapter. It was recommended in the preceding chapter that, pending a systematic evaluation of the available greases, the selection should be based on the MIL-G-21164 and MIL-G-81322 types. Moreover, it is clear that in order to systematize the grease inventory and to obtain the best greases possible, systematic evaluation of the available greases should be made and development of better greases should be encouraged.

The authors are of the opinion that solid-film lubricants as such need not be considered for spline applications. However, solid lubricants as a constituent of the greases and as a constituent of the expendable muffs are well worth careful study.

Summarizing, it is recommended that NASC consider the undertaking of the following programs in the area of lubricants:

a. Systematic evaluation of selected available non-specification greases, with a view to standardization and issuance of new specifications where merited.

b. Development of new greases, particularly those giving superior performance in air environment as well as fuel environment.

APPENDIX A

SUMMARY OF SPLINE WEAR RESEARCH AT SwRI

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1. Introduction

Since 1963, SwRI has been performing a series of research and development programs in furthering an understanding of the mechanisms of spline lubrication and wear, as well as the means of mitigating spline wear. These programs were all performed under contract or sub-contract from the Naval Air Systems Command, Department of the Navy.

The work from 1963 through 1966 was conducted under Contracts NOw-63-0511-d, NOw-64-0341-d, and NOw-65-0224-f under the cognizance of the Power Plant Division, Naval Air Systems Command, with Mr. S. M. Collegeman as project officer. The work was primarily oriented toward a study of lubrication and wear mechanisms. A spline wear tester No. 1 was developed for this investigation to complement the study. This tester has since been employed continuously at SwRI in various subsequent research and development programs.

In 1967, SwRI built and delivered spline wear tester No. 2 to the Aeronautical Materials Laboratory of the Naval Air Development Center, under Contract NOO156-67-C-1302, with Mr. M. J. Devine as project officer. This tester has since been employed in a series of in-house research and development programs at the Naval Air Development Center.

Some time later, the Navy built spline wear tester No. 3 from SwRI-furnished drawings. This tester was operated at the Naval Air Development Center for a period, after which it was loaned to the San Antonio Air Materiel Area to conduct experiments also related to spline wear mitigation.

In the meantime, in 1969, under Contract N00019-69-C-0260, SwRI conducted limited investigations on the effect of plastic coatings on spline wear, in close cooperation with the Naval Air Development Center. This work was under the cognizance of the Materials Division, Naval Air Systems Command, with Mr. S. Weiss as project officer.

In 1970 and 1971, SwRI undertook experimental studies on the effect of certain spline design and material variables on spline wear in a JP-5 fuel environment. This work was performed under subcontract from the AiResearch Manufacturing Company of Arizona, under Contracts N00019-69-C-0404 and N00019-70-C-0362, with Mr. A. Pakvis of AiResearch as project officer.

The various programs undertaken by SwRI, NADC, and SAAMA represent, it is believed, a wealth of information pertinent to the present study. Details of the NADC and SAAMA work are not available at this time. In what follows, a brief summary of the major findings of the SwRI

programs will be given. Details of the various SwRI programs may be found in the following publications:

Weatherford, W. D., Valtierra, M. L., and Ku, P. M., "Experimental Study of Spline Wear and Lubrication Effects," ASLE Transactions, Vol. 9, 1966.

Weatherford, W. D., Valtierra, M. L., and Ku, P. M., "Mechanisms of Wear in Misaligned Splines," Transactions ASME, Vol. 90F, 1968.

Valtierra, M. L., and Ku, P. M., "Research on Mitigation of Spline Wear by Means of Plastic Coatings," SwRI Rept. 539 (under Department of the Navy Contract N00019-69-C-0260), January 5, 1970.

Valtierra, M. L., and Ku, P. M., "Investigation of Spline Wear in JP-5 Fuel Environment," SwRI Rept. 567 (under subcontract from AiResearch Manufacturing Company of Arizona under Department of the Navy Contracts N00019-69-C-0404 and N00019-70-C-0362), March 18, 1971.

2. SwRI Spline Wear Tester

The design of the spline wear tester is shown in Figure A-1 with the details of the spline specimens illustrated in Figure A-2.

In the spline wear apparatus, the splined outer specimen is clamped in a fixed position, and the flanged end of the splined inner specimen is caused to gyrate without rotating, thereby simulating the relative oscillatory motion of a pair of angularly misaligned splines. The gyratory motion is produced by placing a nonrotating gyrator shaft eccentrically within a cylindrical drive shaft which rotates at 4400 rpm. The amount of eccentricity can be controlled and varied. For most of the work reported herein, the eccentricity was such that it resulted in a spline misalignment of 0.006 inch per inch of spline length. To accommodate this misalignment, a diaphragm is used to provide the necessary flexibility between the gyrating shaft and the inner specimen shank. A flexible torque-transmitting rod is attached directly to the flanged end of this shank through the diaphragm. This torque rod is extended upward through the hollow gyrator shaft to a convenient location where the torque is applied. Since the torque rod is mounted vertically, a lever system is provided to allow the application of torsional load with a deadweight. As the spline teeth wear during an experiment, the deadweight gradually moves downward, and the changing position is detected and recorded with a linear variable differential transformer instrumentation system.

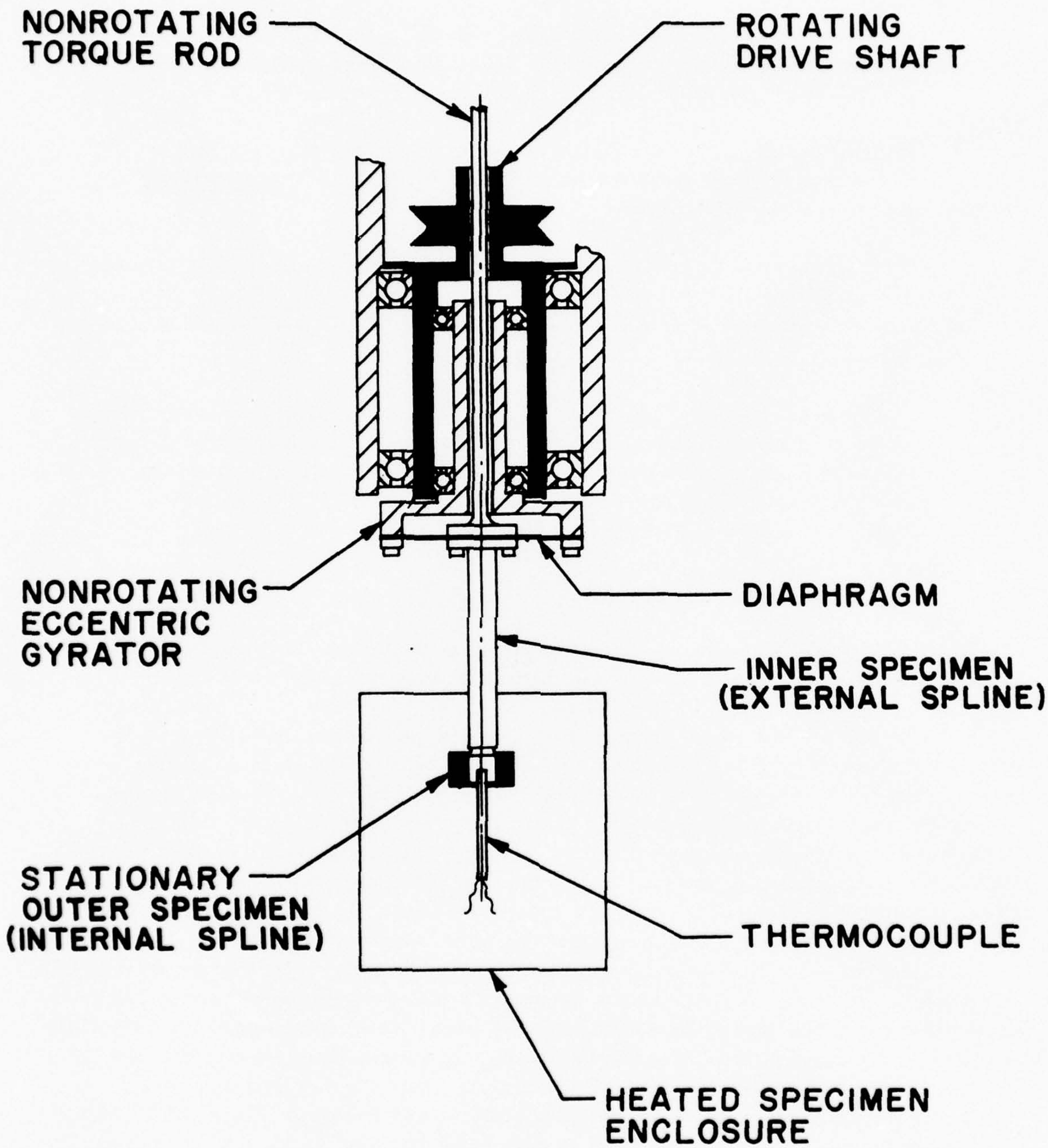
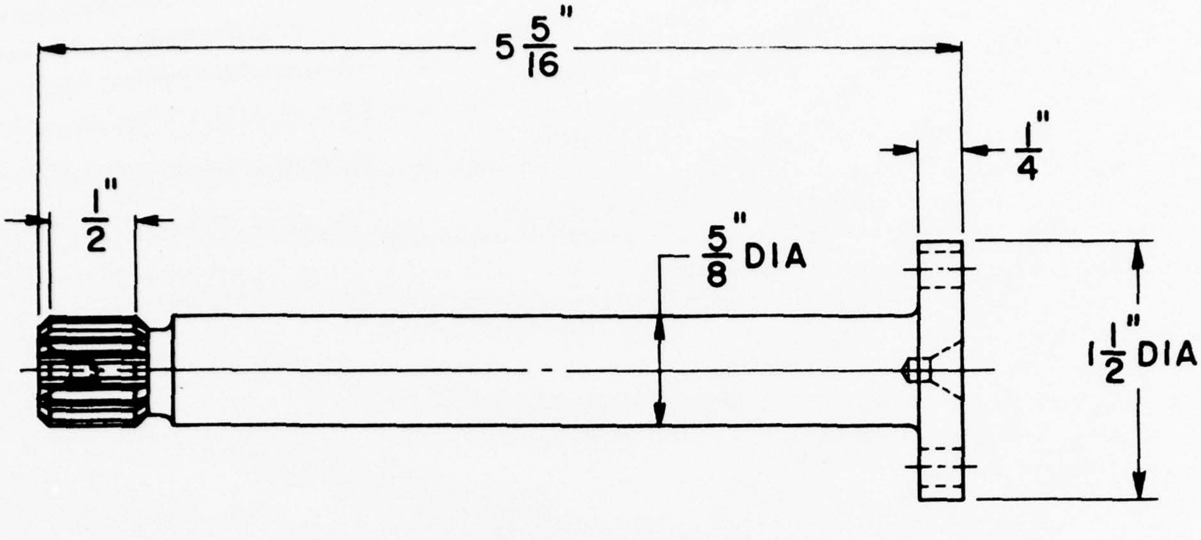
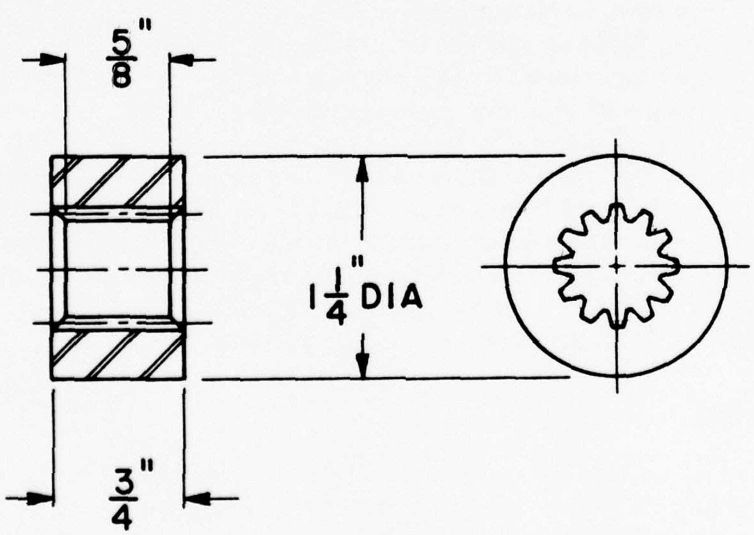


FIGURE A-1. SCHEMATIC REPRESENTATION OF SwRI SPLINE WEAR TESTER



INNER SPECIMEN (EXTERNAL SPLINE)



OUTER SPECIMEN (INTERNAL SPLINE)

FIGURE A-2. DETAILS OF SPLINE SPECIMENS

Spline Specimen Environment. The vertical mounting arrangement of the specimens is provided in order to facilitate operating with either a gaseous or a liquid environment. In either case, the environment fluid is introduced through a preheater coil into the region beneath the spline specimens. It then flows through slots around the splined outer specimen into the region above the specimen. These slots provide a bypass to ensure that lubricant or debris is not forced from between the engaged specimens by the flowing fluid. A bleed system is employed for both gaseous and liquid spline environment fluids. This is provided, in the case of the liquid, in order to preclude equilibrium saturation of dissolved lubricant in the fluid. Spline parts mounted within a jet aircraft fuel pump are continuously exposed to quantities of fresh fuel; hence any spline lubricant which dissolves under such exposure is flushed out with the effluent fuel.

Wear Measurement. A novel aspect of the nonrotating-specimen feature in the described apparatus is that the change in position of the load arm provides a continuous indication of the total spline wear on both specimens without involving interruption of the experiment. In order to establish a quantitative relationship between the spline wear and the change in load arm position, each test specimen has been weighed both before and after each test and the weight loss data have been correlated with the change in load arm position. This relationship has been found, for the constant eccentricity and oscillating frequency used in the work reported here, to be substantially the same for spline types over the entire range of applied torque, with the splines both unlubricated and lubricated with different greases, in both air and fuel environments. The sum of the wear depths on the teeth of the mating splines should be, by construction of the apparatus, almost directly proportional to the change in angular position of the load arm, for the range of angular changes involved. Such is indeed the case, for examination of the worn specimens shows that wear has actually taken place over the entire surface of tooth contact which is, of course, constant. By reason of these considerations, the spline wear has been expressed in terms of wear depth rather than weight loss or change in load arm position, and the spline tooth load in terms of contact pressure rather than as force or torque. These parameters are believed to be more meaningful and can readily be applied to practical design problems.

3. Test Conditions

For the majority of the tests reported herein, the imposed misalignment was 0.006 in./in. The operating temperature was 250°F. The drive shaft speed was 4400 rpm. The applied torque was adjusted to give an average spline tooth load of 3850 psi.

4. Materials and Coatings

Table A-1 summarizes the different materials used for the inner and outer spline specimens. Information is also included relating to the substrate hardness and whether coatings were used.

A description of the two plastic coatings investigated is presented in Table A-2. Teflon-S and Nylon-11 were the only two plastic coatings studied. Since only 0.7 mil of the Teflon-S coating could be applied, both the inner and outer spline specimen teeth were coated. This resulted in a combined coating thickness of about 1.4 mils. The Nylon-11 coating was applied to the inner specimen only. A coating thickness of about 10 mils was used.

Several metallic coatings were investigated in the presence of JP-5 fuel and are described in Table A-3. All of these nominal one-mil thick coatings were applied to the inner specimens only.

5. Lubricants

A tabulation of some of the greases studied is contained in Table A-4. A large number of other greases studied are not included in the interest of space.

Considerable work was also done on liquid lubricants, mainly in connection with the mechanism studies. However, in the interest of space, these will not be discussed here. As remarked in the main text, spline wear in the presence of a liquid lubricant is minimal and has not been a major operational problem. The major problem has been with interface splines, which are generally lubricated with greases for reasons of convenience, simplicity, and system weight.

Solid-film lubricants were also investigated, as shown in Table A-5. These films were applied to the inner specimen (male spline) in the experiments.

6. Mechanism of Spline Wear

The mechanism of wear of misaligned splines was briefly explained in the main body of this report. However, in order to provide a proper "birdseye view" of the experimental results to be presented in the subsequent paragraphs, it is desirable to consider the wear mechanism once again at this juncture.

TABLE A-1. SPLINE SPECIMENS USED IN SwRI PROGRAMS FROM 1963 TO 1971

Code	Pitch	No. of Teeth	Material Male	Material Female	Hardness, R_c Male	Hardness, R_c Female	Male Spline Coatings	Remarks
Type 1	20/40	12	AMS 6260	AMS 6260	51-55	58-62	No	
Type 2	20/40	12	AISI 4130	AISI 4130	28-32	33-37	No	
Type 2A	20/40	12	AISI 4130	AISI 4130	28-32	33-37	No	Type 2, 2nd batch
Type 2B	20/40	12	AISI 4130	AISI 4130	28-32	33-37	Yes	Type 2, 3rd batch
Group II	20/40	12	AISI 4130	AISI 4130	29-34	34-37	No	
Group II	24/48	15	AISI 4130	AISI 4130	29-32	32-38	No	
Group II	32/64	20	AISI 4130	AISI 4130	26-32	36-39	No	
Group III	20/40	12	M50	AISI 4130	56-65	36-41	Various	
Group IX	20/40	12	AISI 4130	AISI 4130	28-32	33-37	No	Crowned male
Group XIII	20/40	12	M50	AISI 4130	62-65	36-38	Yes	Crowned male

TABLE A-2. DESCRIPTION OF PLASTIC COATINGS INVESTIGATED

Teflon-S. This relatively new fluorocarbon coating has the advantage of being a tough self-lubricating material. It has been used in various practical applications where a low coefficient of friction is required, such as in the use of power circular and handsaws. It is relatively stable at temperatures up to 450°F and is compatible with some jet fuel environments. Teflon-S coatings can only be applied in a thickness of 0.7 mils due to the application techniques and the size of the Teflon particles. A nominal coating thickness of 0.7 mils was applied to both the inner (male) and outer (female) spline specimens.

Nylon-11. Nylon-11 coating can be applied in a thickness range of about 8 to 30 mils by a fluid-bed process. The mass of the specimen to be coated and the duration of immersion control the thickness of the coating. A nominal coating thickness of 10 mils was selected and applied to the standard inner spline specimens. In order to provide sufficient clearance between the mating splines, the outer (female) spline specimen was broached larger.

TABLE A-3. DESCRIPTION OF METALLIC COATINGS INVESTIGATED

Electroless Nickel I and II. The electroless nickel coatings were applied by AiResearch by a proprietary process. Two types were evaluated: Electroless Nickel I was applied without a subsequent heat treatment. Electroless Nickel II was applied with a subsequent heat treatment.

Silver. This coating was also applied by AiResearch in accordance to a proprietary specification.

X. This metallic coating is proprietary and was applied by a vendor.

Y. This metallic coating is also proprietary and was applied by a vendor.

All above coatings were applied only to the inner (male) specimens to a nominal thickness of 0.001 inch.

TABLE A-4. DESCRIPTION OF SOME GREASES INVESTIGATED

	Composition				
Code	Thickener	Oil Type	Inhibitors-Additives	Solubility in Fuel, %*	Remarks
A	Clay (treated)	Mineral	Oxidation, corrosion	86.3	MIL-G-7711A
B	Lithium soap	Diester-mineral	Oxidation, corrosion, MoS_2	88.9	MIL-G-21164B
C	Dye	Fluoro-silicone	--	21.8	MIL-G-27617
D	Silica (treated)	Mineral	Corrosion, MoS_2	80.1	MIL-G-23549
E	Clay (treated)	Mineral	MoS_2	87.4	Proprietary
F	Clay (treated)	Mineral	Oxidation, corrosion	73.2	MIL-G-25537A
G	Calcium soap	Mineral	Oxidation, corrosion, MoS_2	71.9	Grease F with 5% MoS_2 added
I	Nonsoap	Fluoro-carbon	--	--	Experimental (MIL-G-27617 type)

*Determinations made with MIL-S-3136, Type II fluid in accordance with the solubility test prescribed in MIL-G-27617.

TABLE A-5. DESCRIPTION OF SOLID-FILM LUBRICANTS INVESTIGATED

Code	Description	Remarks
K	Air-dried MoS_2 film.	MIL-L-23398
L	Baked-on MoS_2 film.	MIL-L-8937
M	Experimental film: MoS_2 powder, graphite powder, NaSi, and H_2O. Air and oven-dried between successive coats.	Developed by NADC (NAEC-AML-23A)

All films were applied by the Naval Air Development Center. A nominal film thickness of 0.0002-0.0005 in. was applied to the inner (male) specimen only.

The fretting type of wear process as experienced in splines comprises a period of negligible wear known as an "induction period", followed by a period of rapid wear in which the wear rate is essentially linear. The induction period has been established to be chemical in character and may be enhanced by use of suitable antioxidants or corrosion inhibitors. The rapid wear period is essentially mechanical in character, and the wear rate is influenced more by materials and surface treatments and the relative amount of sliding (i. e., misalignment or high speed) than by either the lubricant or the other operating variables. To minimize total wear, it is of course desirable to employ lubricants of long induction period.

Figure A-3 portrays the behavior described. Case B in this figure shows the wear behavior in dry air without any lubricant present. In this case, wear commences immediately upon the start of oscillatory motion, and proceeds at a linear rate.

Case A illustrates the behavior with a noninduction-period grease, which also gives immediate and linear rate of wear, but the rate of wear is noticeably, though only slightly, higher than the unlubricated case. This is because the grease tends to retain the wear debris in the contact zone, which oxidizes or partially oxidizes to form hard oxides to cause abrasive wear.

With an induction-period grease, as illustrated by Case C, there is first an induction period of negligible wear. After the chemical constituents in the fixed amount of grease are used up, there follows a period of rapid wear, with a wear rate similar to that of Case A (noninduction-period greases). It has been found that if at the end of the induction period, the used grease is removed and the splines cleaned and recharged with fresh induction-period grease, the period of negligible wear will repeat. In other words, with continued replenishments of fresh induction-period grease, negligible wear will continue to be obtained.

If the splines are lubricated with a fixed and limited amount of a noninhibited oil (no induction period), the wear behavior would be as illustrated by Case D. Without an induction period, wear commences immediately upon the start of relative motion. However, in this case, the wear rate, while also linear, is very low because the

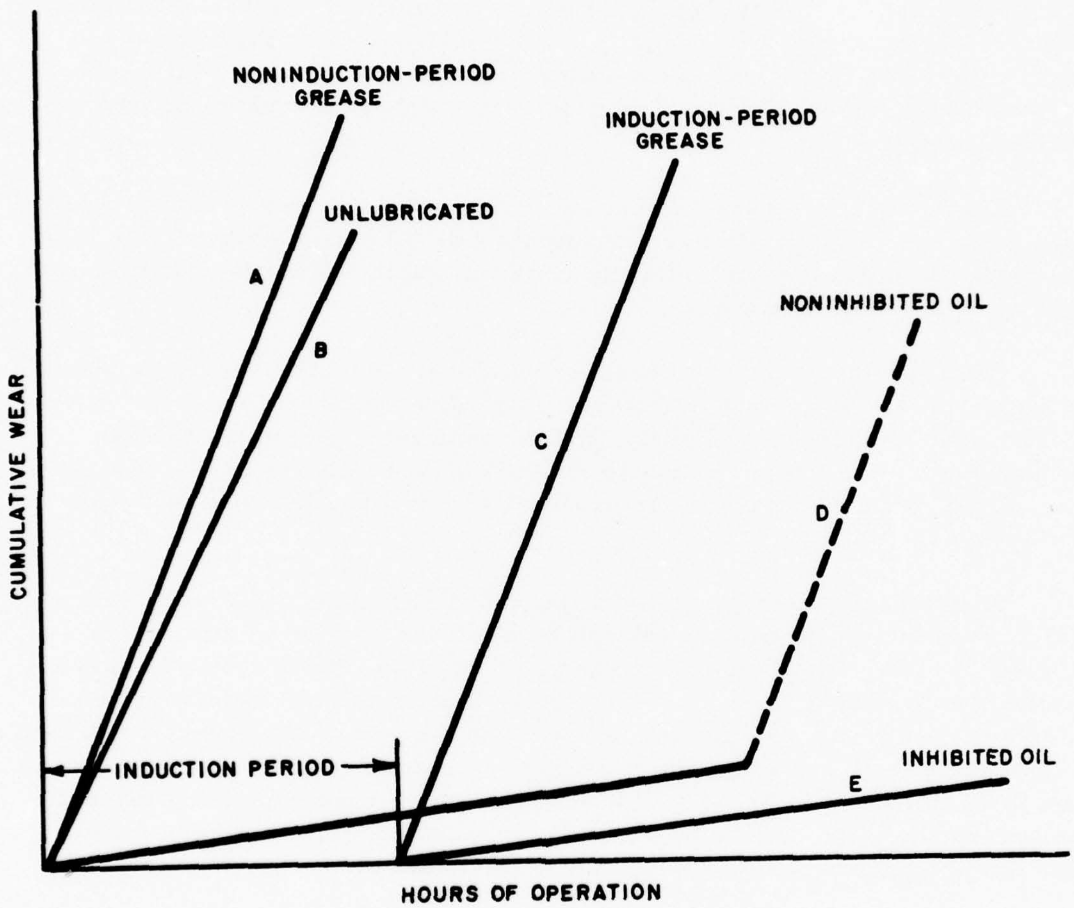


FIGURE A-3. GENERAL BEHAVIOR OF SPLINE WEAR IN DRY AIR

presence of the liquid tends to help carry the wear debris away from the contact zone. Further, presence of oil tends to minimize the oxidation of the wear debris. However, after the liquid has been "pushed away" from the contact zone by the repeated oscillatory motion, there is no more lubricant present and hence a period of rapid wear ensues, much as in the unlubricated case.

If the fixed and limited amount of the liquid lubricant contains suitable additives to provide an induction period, then the behavior would be as shown by Case E. There will first be a period of negligible wear. After the chemical constituents in the oil are consumed, a period of appreciable wear will take place. The wear rate is similar to that in Case D since the liquid tends to carry the wear debris away from the wear zone and also minimizes wear debris oxidation. On the other hand, if the liquid supply is large, or if the oil lubrication is continuous, then negligible wear will continue.

Solid-film lubricants have been found to behave similarly to the unlubricated case (Case B). Solid films are generally very thin and provide almost no protection against wear under these conditions. However, the loose wear debris will move away from the contact zone, because there is no grease to retain them there.

In what follows, the effects of various lubricants, spline materials and coatings, design variables, and operating variables will be discussed.

7. Effect of Greases

Figure A-4 presents the comparative performance of Type 2 splines, unlubricated and lubricated with several greases in dry air and JP-5 environments. The abscissa denotes the time required to reach a certain amount of total spline wear in dry air environment; the ordinate denotes the time required to reach the same amount of total wear in JP-5 environment. The various lines portray the performance of splines with no lubrication (none) and with various greases (A, B, C, etc.). For each of the lines shown, three data points are given that correspond to different amounts of total

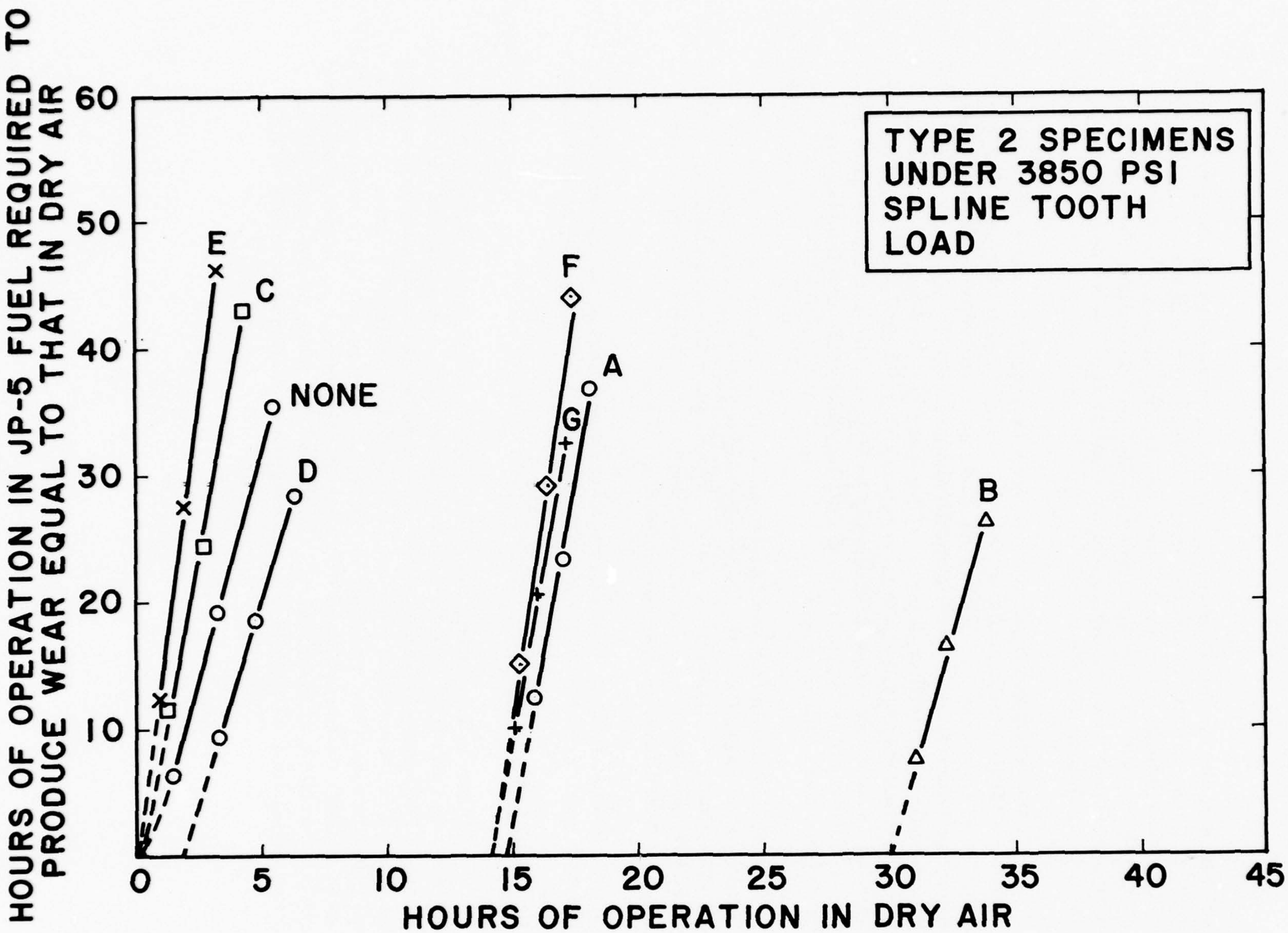


FIGURE A-4. PERFORMANCE OF GREASES IN DRY AIR AND JP-5 ENVIRONMENTS
(TYPE 2 SPLINES)

spline wear. For each line, the first point reckoned from the abscissa represents a total wear of 0.003 inch. Similarly, the second and third points represent a total wear of 0.006 inch and 0.009 inch, respectively. Thus, for unlubricated splines, the total wear reaches 0.009 inch after 6 hours of operation in dry air, while in JP-5 fuel it takes 36 hours of operation to reach the same amount of wear. Likewise, with splines lubricated with Grease B, this same amount of wear is reached after 34 hours of operation in dry air, but 26 hours of operation in JP-5.

No induction periods are observed for no lubrication and for Greases C and E. Hence the lines for these cases pass through the origin. With all other greases, induction periods are observed in dry air but not in fuel. Hence the lines for these cases intercept the abscissa, the intercepts being the lengths of the induction periods.

Figure A-4 shows that, with the exception of Greases C and E, the performance of a grease in dry air is primarily dictated by the magnitude of its induction period in dry air. Further, with the exception of Grease C, E, and F, the performance of all other greases in a JP-5 environment is somewhat poorer or else does not differ greatly from that of the unlubricated case. Of the three greases that show performance in fuel definitely superior to that in air environment, the performance of Grease C may, as noted earlier, be accounted for by its low solubility in fuel. However, the behavior of Greases E and F in fuel cannot be explained on this basis. Since these greases are proprietary in nature and their precise compositions are not known, no conclusions can be made at this time.

8. Effect of Solid-Film Lubricants

Experiments were also performed to determine the effectiveness of three solid-film lubricants. The three solid films are identified in Table A-5. All of the films were applied by the Naval Air Development Center and the nominal film thickness was 0.0002-0.0005 inches.

Figure A-5 illustrates the results obtained with the K, L, and M solid-film lubricants operated in a dry air environment. It is evident that the solid films did not provide any protection for the spline connection and were essentially the same as the uncoated reference test. Tests were also performed (not included here in the interest of space) for the Type 1 specimens with K, L, and M solid films applied. The results of these tests were also essentially the same as those presented in Figure A-5; the solid-film lubricants have been found to behave similarly to the unlubricated case. Solid-films are generally very thin and provide almost no protection against wear under these conditions. The loose wear debris will work away from the contact zone, since there is no grease to retain them there.

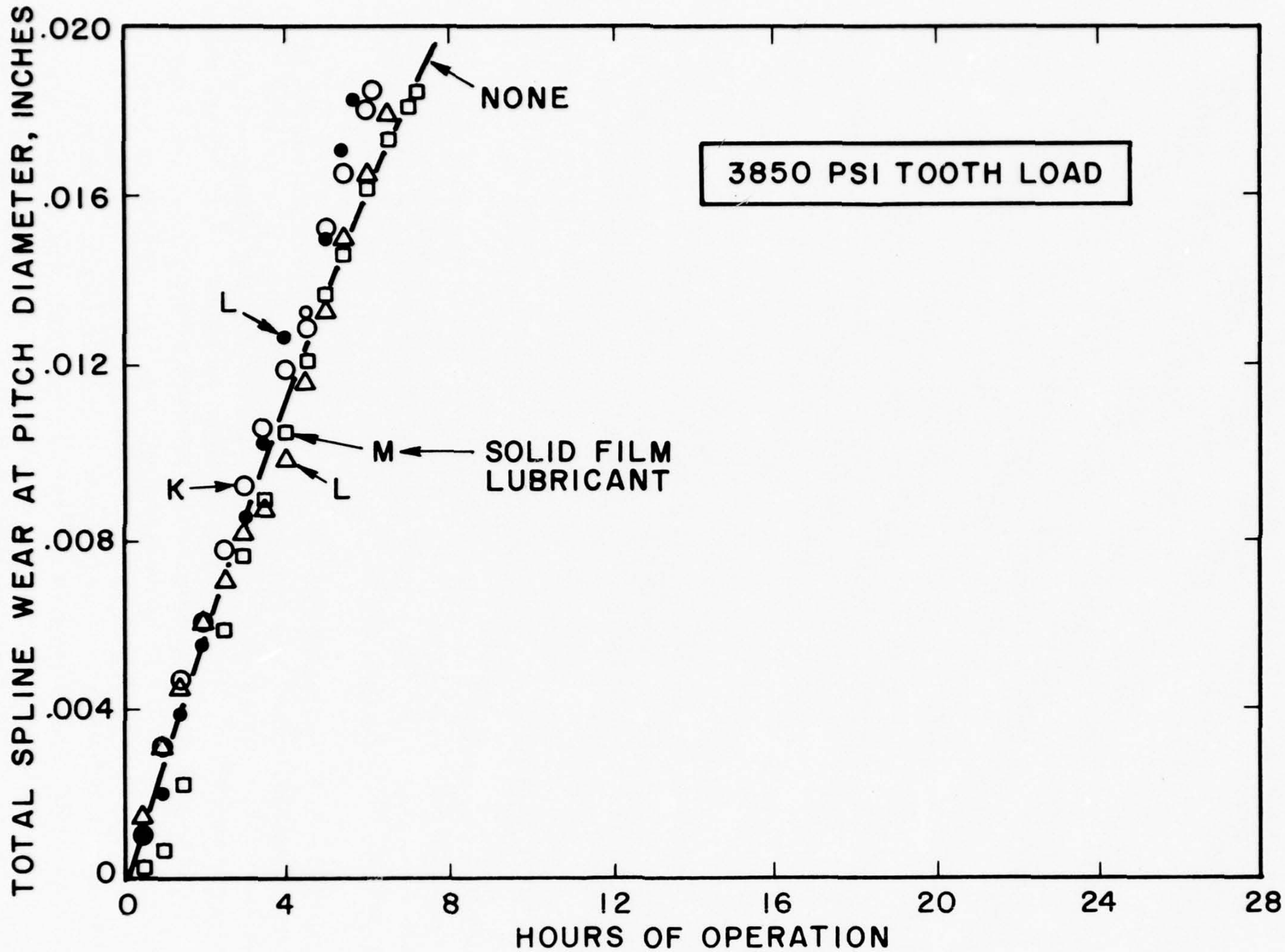


FIGURE A-5. PERFORMANCE OF SOLID-FILM LUBRICANTS IN DRY AIR (TYPE 2 SPLINES)

9. Effect of Fuels

Investigations have been conducted with the spline specimens surrounded by JP-5 and JP-6 fuels, rather than by air. In all cases, whether the splines are lubricated with a grease or unlubricated, no period of negligible wear is found to exist when fuel is present. In other words, the presence of fuel tends to wash the grease away from the contact zone, thus removing the induction period, resulting in immediate wear. This wear rate is, however, lower than in dry air (i. e., without fuel present), in much the same way as the presence of a liquid lubricant.

Unlubricated with Grease. Referring to Figure A-6 for unlubricated splines (a case of no induction period), the presence of fuel mitigates spline wear, due partly to the lubricating effect of the fuel, partly to the fact that the fuel tends to exclude oxygen from the contact area thereby minimizing oxidation of the wear particles to form abrasive oxides, and partly to the fact that the fuel tends to enhance removal of the wear particles and their oxides from the contact area. The smaller beneficial effect of JP-6, as compared to JP-5, is probably due to its inferior lubricating quality, as it is a more highly refined fuel.

Lubricated with Grease. For splines lubricated with grease, the presence of fuel tends to dissolve the grease and remove it from the contact area. Thus, the spline wear behavior with fuel present tends to approach that of the unlubricated case. Hence the performance of Grease C, which exhibits no induction period, tends to be qualitatively similar to the unlubricated case, as shown in Figure A-7. Here, the relatively superior performance of the grease in JP-5 and JP-6 is probably due to the fact that Grease C is the least soluble of all of the greases evaluated (see Table A-4). Therefore, the lubricating quality of the fuel is being augmented by that of the grease, while the presence of fuel effectively minimizes the availability of oxygen to the contact area to form abrasive oxides.

The performance of greases that show induction periods in dry air is illustrated in Figure A-8 for Grease A. The disappearance of an induction period in the presence of fuel is believed to be due to the solubility effect of the fuel, as Grease A is highly soluble in fuel (see Table A-4). The relative performance in dry air and in fuel is dependent upon the magnitude of the induction period in air. However, the relative effects of JP-5 and JP-6 are preserved as explained previously.

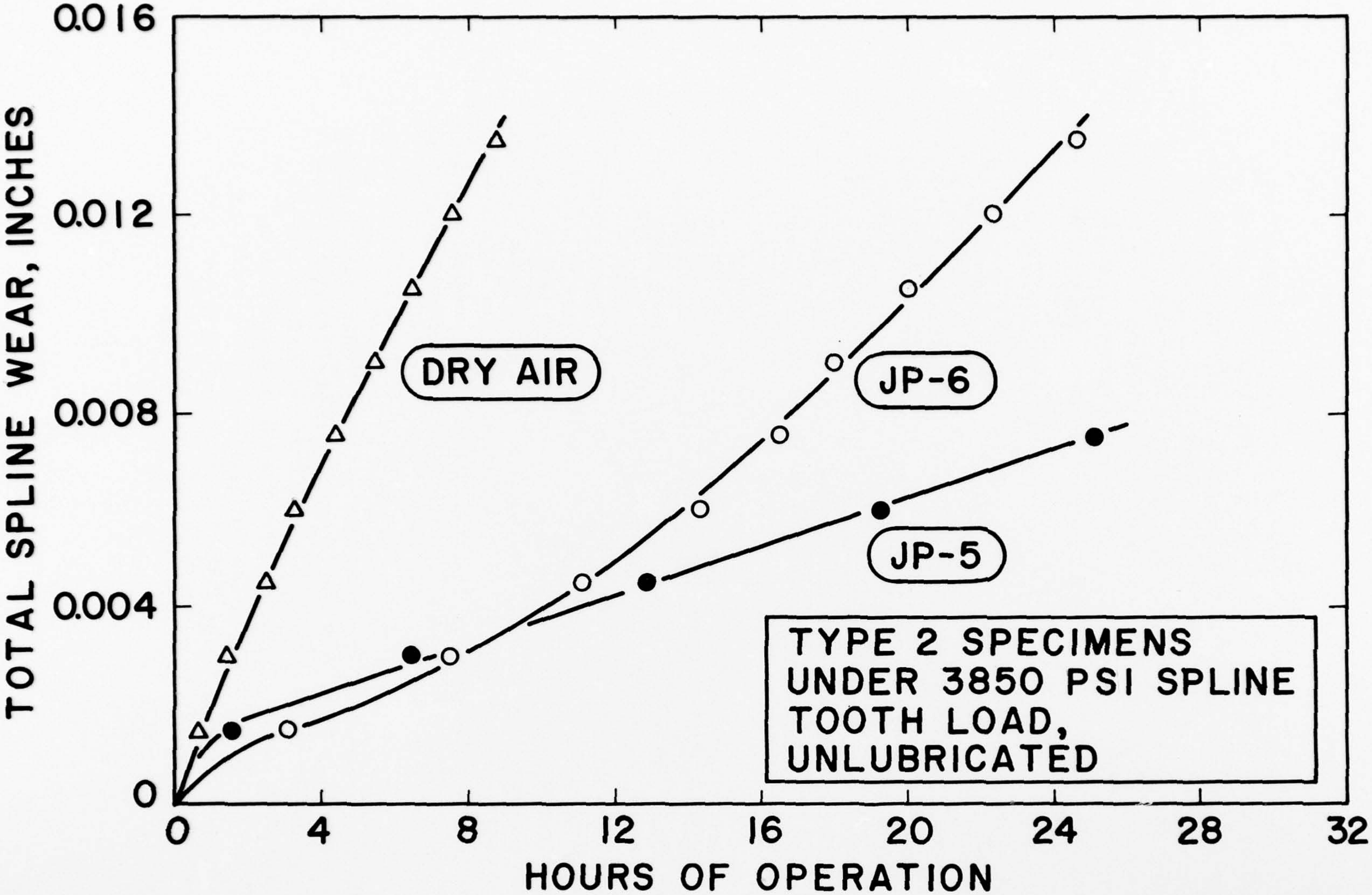


FIGURE A-6. INFLUENCE OF SPLINE ENVIRONMENT FLUID ON WEAR RATES FOR UNLUBRICATED SPLINES (TYPE 2 SPLINES)

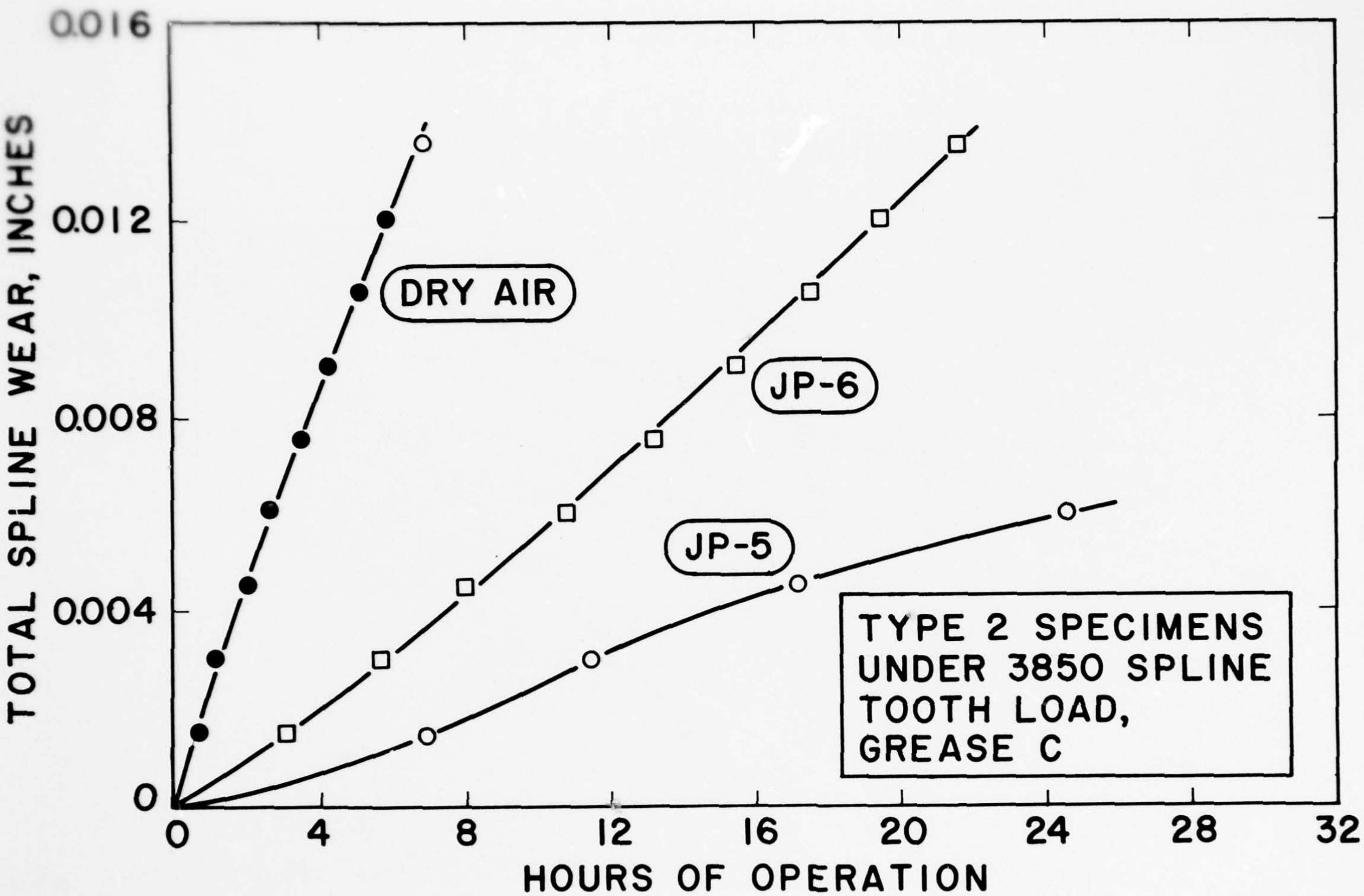


FIGURE A-7. INFLUENCE OF SPLINE ENVIRONMENT FLUID ON WEAR RATES FOR SPLINES LUBRICATED WITH GREASE C (TYPE 2 SPLINES)

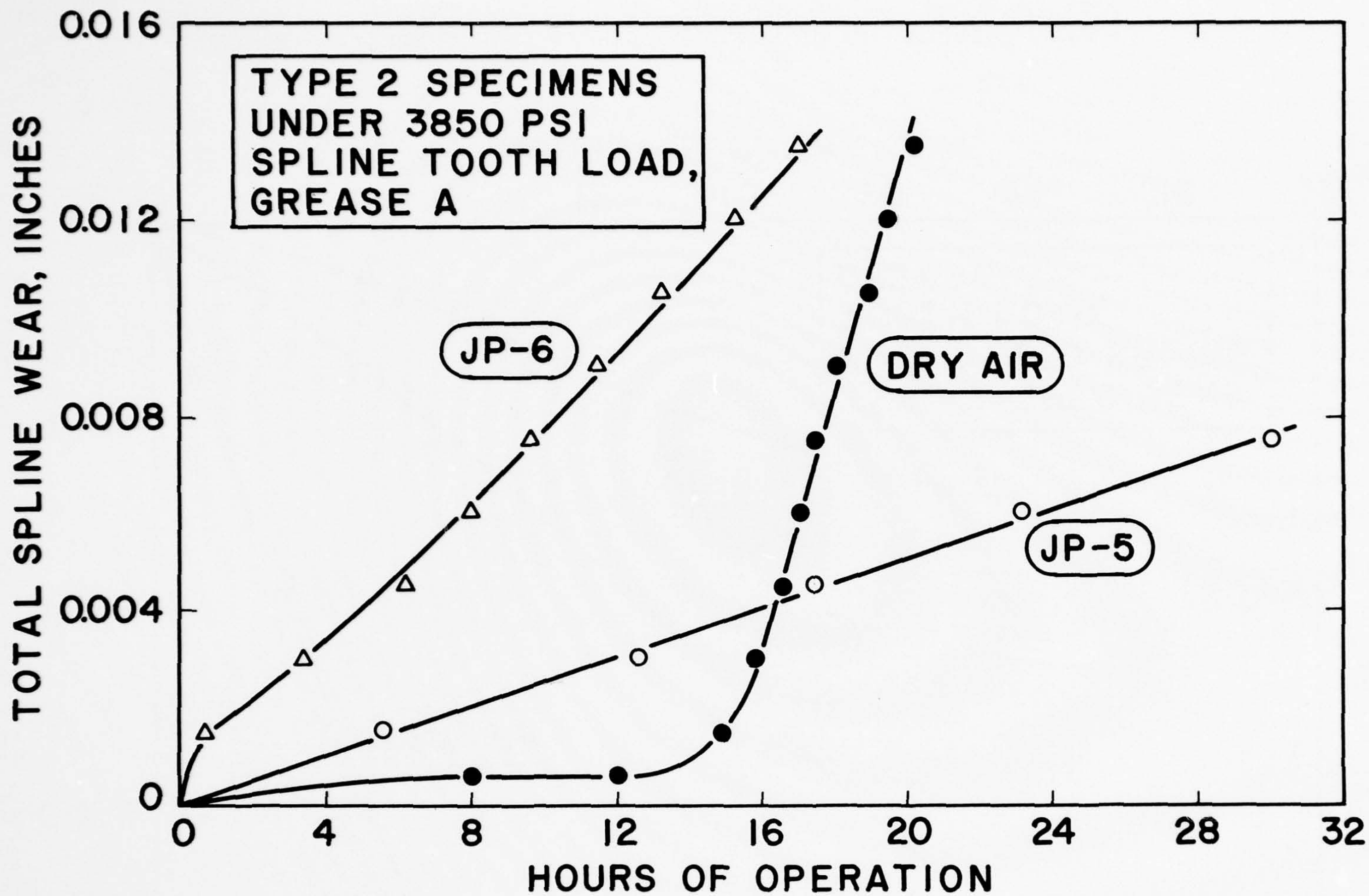


FIGURE A-8. INFLUENCE OF SPLINE ENVIRONMENT FLUID ON WEAR RATES FOR SPLINES LUBRICATED WITH GREASE A (TYPE 2 SPLINES)

10. Effect of Misalignment

Figure A-9 shows the important effect of misalignment on spline wear. With Grease A in dry air, the induction period was 15 hours at an oscillation amplitude of 0.006 inch/inch of spline length. When this oscillation amplitude is reduced to 0.0045 inch/inch, the induction period is increased to 55 hours, or about 350 percent. Although no experiments were performed with still reduced misalignment, the beneficial effect of controlling misalignment is obvious.

Figure A-9 also compares the effects of dry nitrogen, dry air, moist nitrogen, and moist air. These effects, though also significant, will not be discussed here in the interest of space.

11. Effect of Spline Tooth Load

For unlubricated splines operating in dry air, the wear on the spline teeth has been found to begin immediately upon commencing the test and, for a given tooth load, to continue at a nearly constant rate with time. This is illustrated for the Type 2 specimens in Figure A-10. This figure also shows that increasing the tooth load decreases the wear rate. This is because an increase in tooth load reduces the true slip between the teeth for the same apparent slip or misalignment. However, as shown in Figure A-10, the effect is small in this case.

The wear behavior of Type 2 splines in dry air lubricated with Grease A, B, D, F, or G differs drastically from the general pattern discussed above. The behavior shown in Figure A-11 for Grease A is typical of these greases. With each of these greases and for a given tooth load there exists, upon the start of the test, an induction period in which negligible wear takes place. After this induction period, the wear rate increases until it reaches a nearly constant value which has, in every case, been greater than that experienced with unlubricated splines at corresponding tooth load. Decreasing the tooth loading lengthens the induction period. In other words, the use of a low tooth load in design is desirable.

12. Effect of Surface Roughness

Using Grease A, a series of experiments was conducted to investigate the influence of spline-tooth surface roughness on wear behavior. This study employed smooth new specimens (7-9 rms) and specimens roughened by vapor blasting (80-125 rms) with a quartz grit.

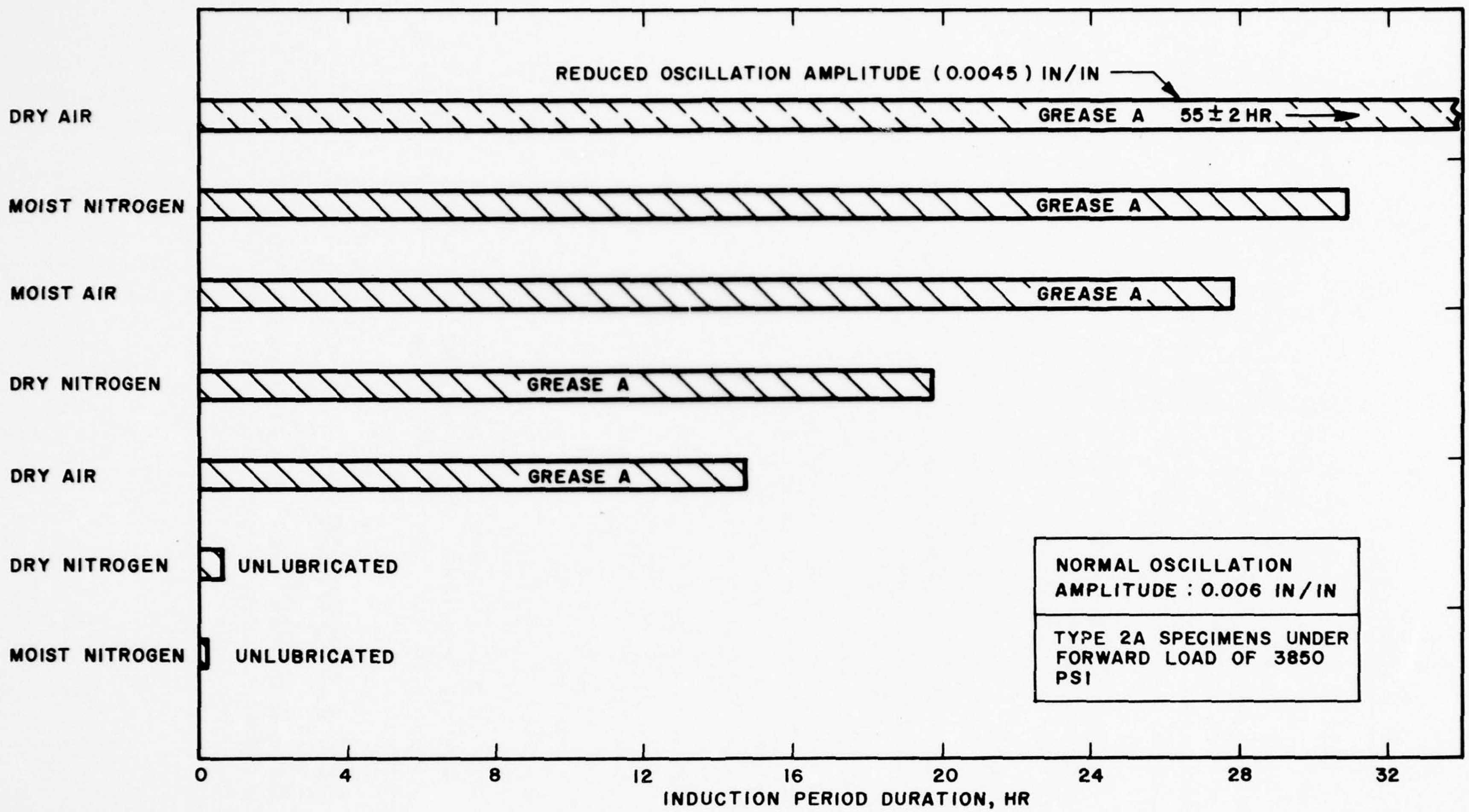


FIGURE A-9. EFFECT OF SPLINE MISALIGNMENT AND GASEOUS ENVIRONMENT (TYPE 2A SPLINES)

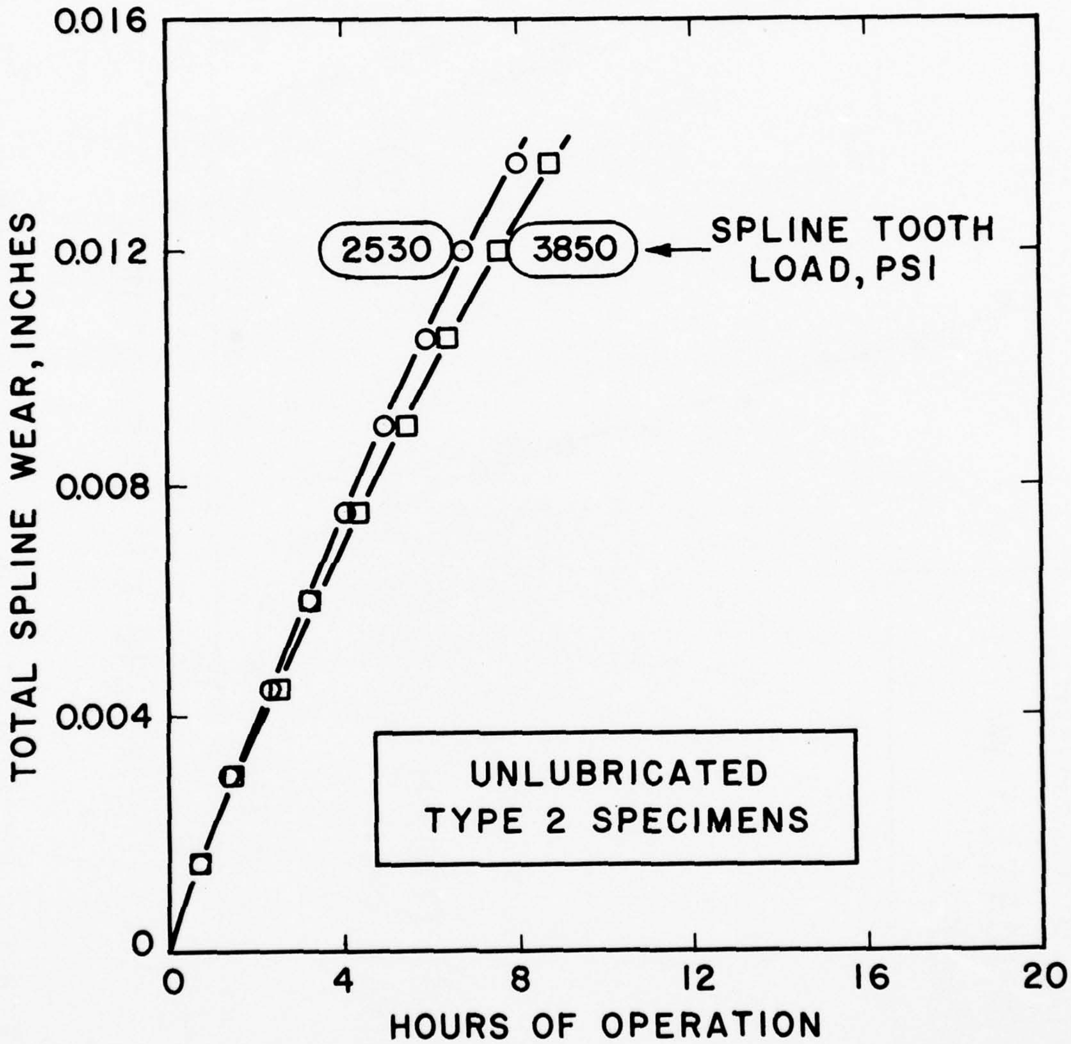


FIGURE A-10. INFLUENCE OF LOAD ON SPLINE WEAR RATES IN DRY AIR FOR UNLUBRICATED SPLINES (TYPE 2 SPLINES)

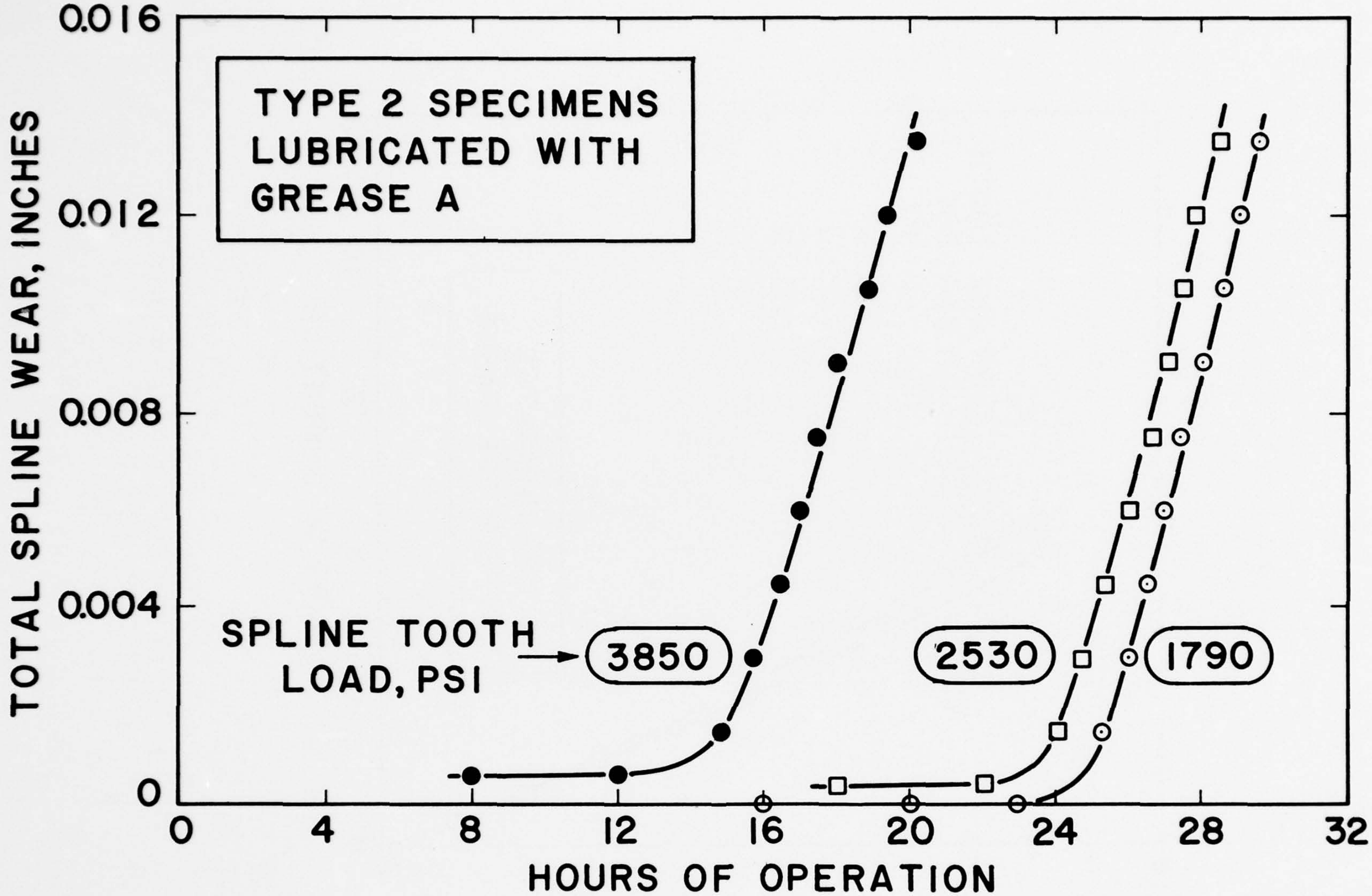


FIGURE A-11. INFLUENCE OF LOAD ON SPLINE WEAR RATES IN DRY AIR FOR SPLINES LUBRICATED WITH GREASE A (TYPE 2 SPLINES)

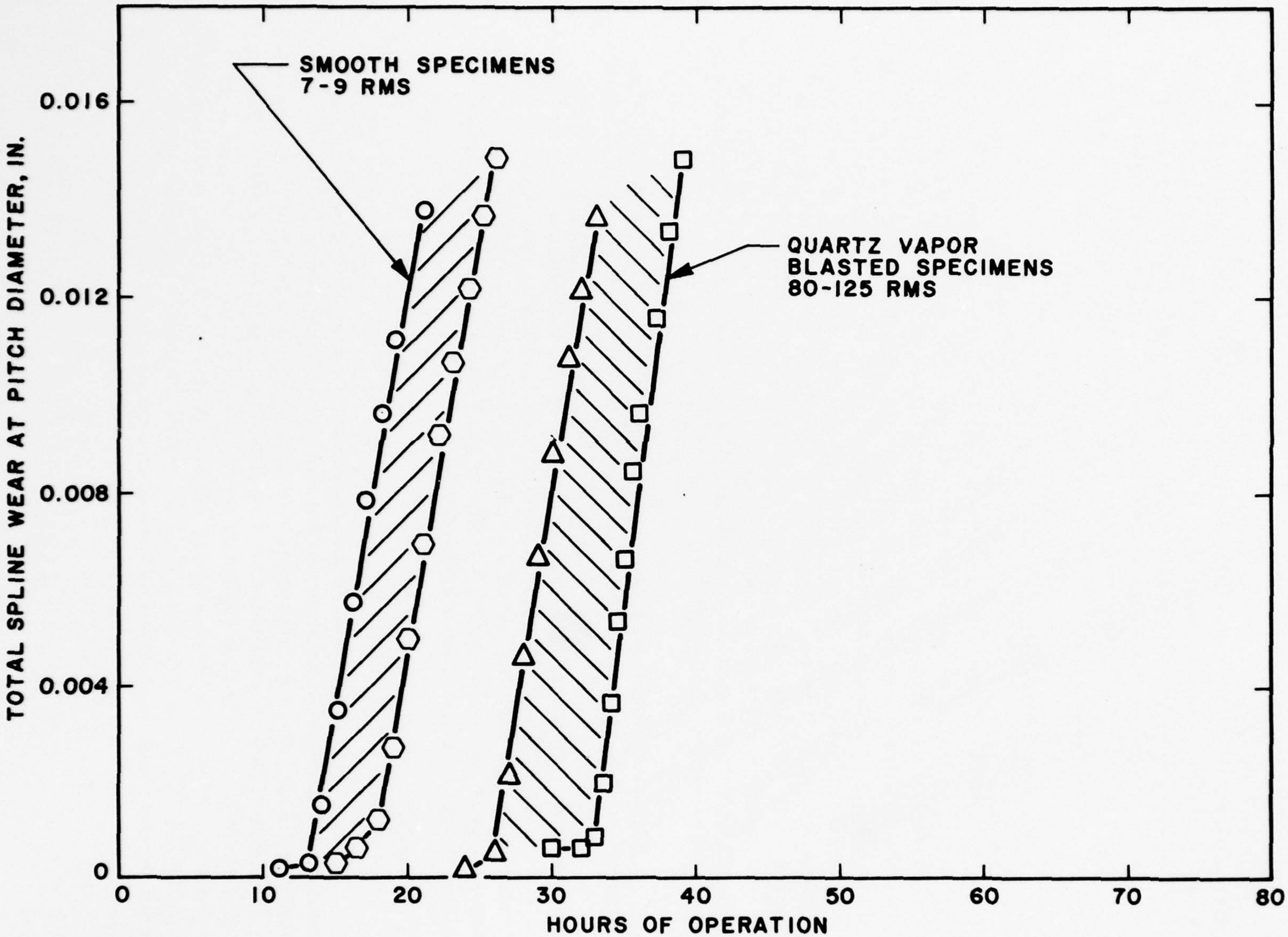


FIGURE A-12. INFLUENCE OF SURFACE ROUGHNESS FOR SPLINES IN DRY AIR LUBRICATED WITH GREASE A (TYPE 2 SPLINES)

The results presented in Figure A-12 indicate that roughening of the spline-tooth surfaces increased the induction period. This is attributed to the greater grease holding capacity with rougher surfaces, which also facilitates grease flow to provide lubrication. Although the induction period with the roughened specimens was almost twice that of the smooth specimens, the wear rates after the induction period were essentially the same. Analogous results were observed when used specimens (i.e., specimens roughened by wear rather than by vapor blasting) were employed.

13. Effect of Tooth Pitch

Figure A-13 presents a summary of the Group II tests in the form of the average hours of operation to various amounts of total wear at the pitch diameter as a function of the number of spline teeth in JP-5 fuel. From the results it can be seen that at a relatively low total wear of 0.004 in. the wear life increased with a reduction in the number of spline teeth, with the effect being very small. At larger amounts of total spline wear, the beneficial effect of reducing the number of spline teeth became more apparent. Based on good repeatability of the Group II spline wear tests, the best spline combination appeared to be the 20/40 pitch, 12-tooth splines. It should be noted that this was the same design used in all of the previous programs performed at SwRI.

The lower three sets of bargraphs presented in Figure A-14 illustrate the individual tests from which Figure A-13 was derived. As indicated, good repeatability was obtained within each of the different tests. The bargraphs indicate the relative ratings of the different tests with information on the amount of wear obtained at corresponding test times. The circle at the ordinate indicated no spline wear at the start of the test, while the next three symbols ($\triangle$, $\square$, ∇) indicate the total spline wear obtained at 0.004, 0.008 and 0.012-in., respectively.

14. Effect of Tooth Crown

The upper three sets of bargraphs in Figure A-14 illustrate the results of the tests performed on three different crown radii: 11.25, 14.50 and ∞ in, also in JP-5 fuel. As can be seen, a moderate increase in the wear rate was present with a reduction in the crown radius. The increase in wear rate was probably due to the increase in tooth contact pressure. There was only a slight advantage of the 14.50 in. crown radius over the 11.25 in. crown radius. The added clearance provided by crowning the inner specimen produced an unequal depth of engagement

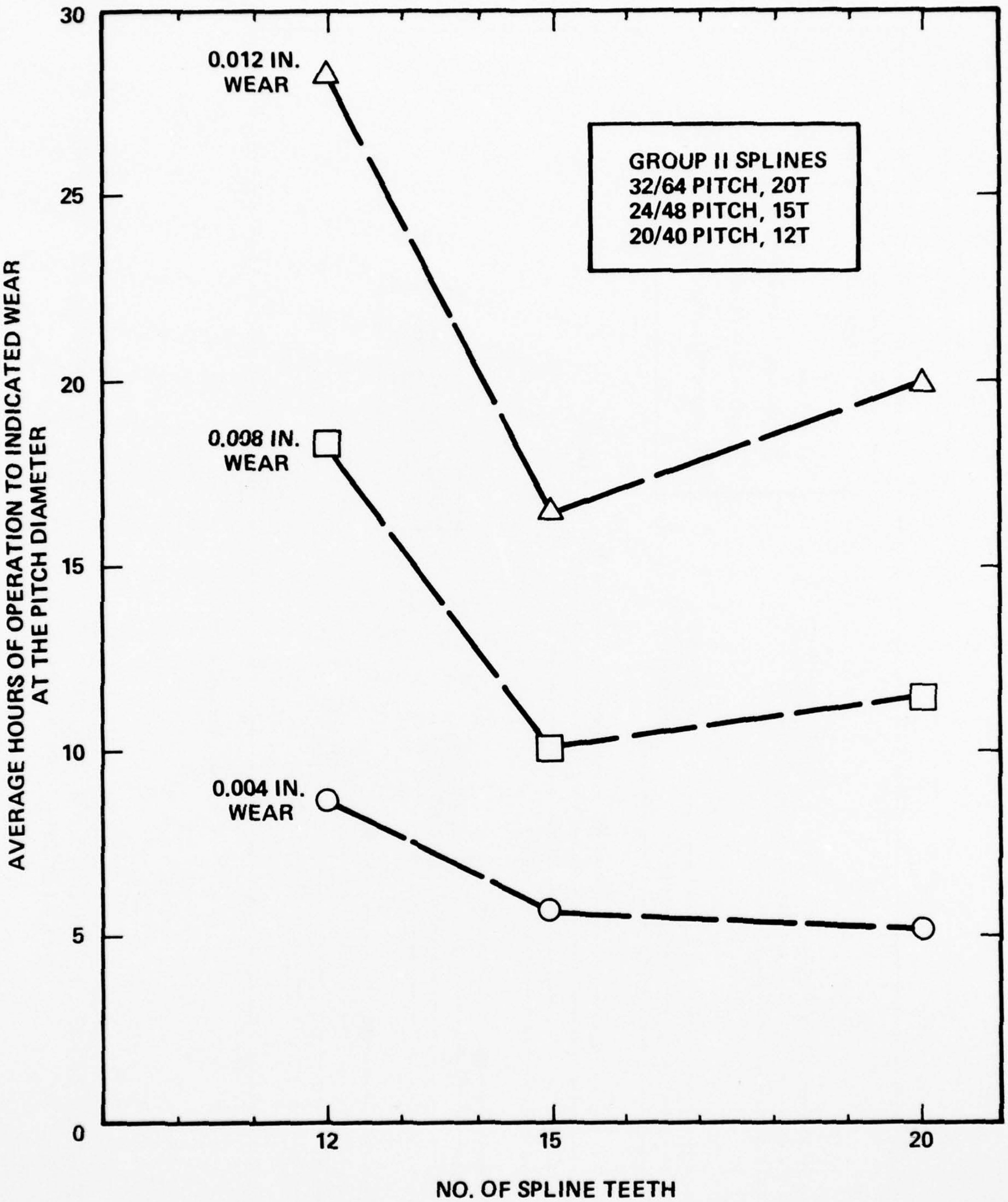


FIGURE A-13. INFLUENCE OF TOOTH PITCH FOR SPLINES IN JP-5 FUEL (GROUP II SPLINES)

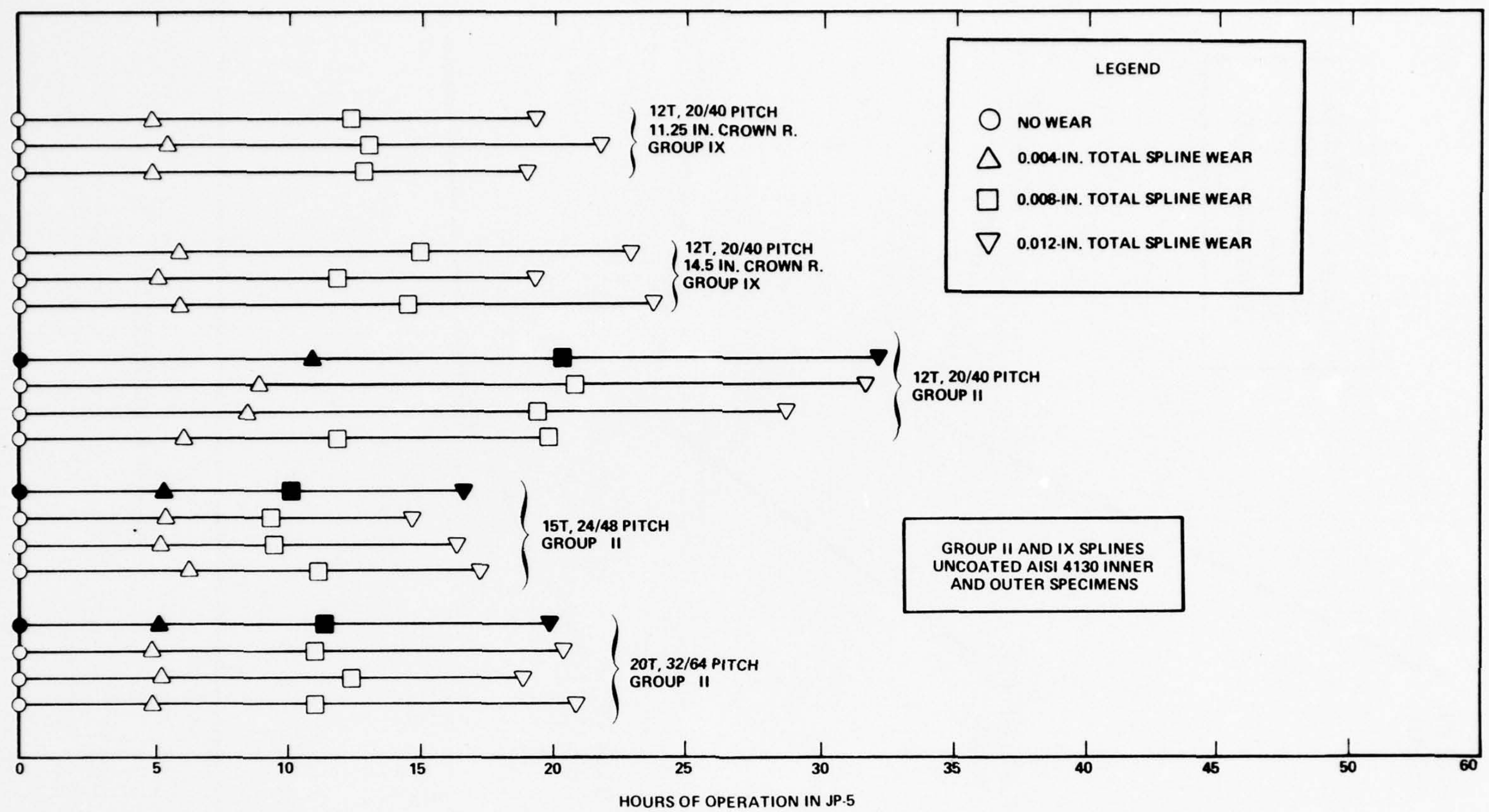


FIGURE A-14. INFLUENCE OF TOOTH PITCH (GROUP II SPLINES) AND CROWNED SPLINES (GROUP IX SPLINES) IN JP-5 FUEL

within the spline connection. Apparently, the inner specimen moved radically within the outer specimen producing a greater amount of tooth contact on about half of the spline teeth. This was observed on all of the 11.25 and 14.50 in. crown radii spline specimens and not on the uncrowned Group II spline specimens.

15. Effect of Spline Materials

The wear life can be substantially affected by the material used. Figure A-15 compares the performance in JP-5 fuel of spline sets employing AISI 4130 steel for both male and female specimens (see Table A-1, Group II) with those employing M50 male and AISI 4130 female specimens (Group III). At a total wear of 0.012 inch, the sets with AISI 4130 male specimens gave an average operating time of 27 hours, while those with M50 male specimens lasted an average of 96 hours.

Experiments were also performed for spline sets with AMS 6260 male and AMS 6260 female specimens (see Table A-1, Type 1) in JP-5 fuel. These splines gave less than 0.001 inch of total wear in 147 hours at 3850 psi tooth load. In contrast, Figure A-15 shows that, for the same tooth load and total wear, spline sets with AISI 4130 male and female specimens (Group II) gave only 5 hours, while spline sets with M50 male and AISI 4130 female specimens (Group III) gave only 15 hours. Unfortunately, due to the nature of the program, no determination was made for spline sets with both male and female specimens made of M50 steel, thus the performance of M50 versus M50 in fuel is not known. The very superior performance of AMS 6260 steel in fuel is, however, obvious.

16. Effect of Plastic Coatings

Experiments were also performed to investigate the effectiveness of two plastic coatings, Teflon-S and Nylon-11. The coatings were applied to Type 2B male splines made of AISI 4130 steel to the same specifications as those used in the prior work (see Table A-1), in combination with uncoated AISI 4130 female splines.

Dry Air Environment. Table A-6 summarizes the average results obtained in a dry air environment, for the various combinations of coatings and greases covered in this program.

With uncoated, Teflon-S coated, and Nylon-11 coated splines operated without grease in dry air, no induction period was observed, and the wear rate was essentially constant in every case. The total wear at the end of 5 hours was 0.011 inch for both uncoated and Teflon-S coated splines, and 0.007 inch for Nylon-11 coated splines. The similarity in performance for uncoated and Teflon-S coated splines was apparently due

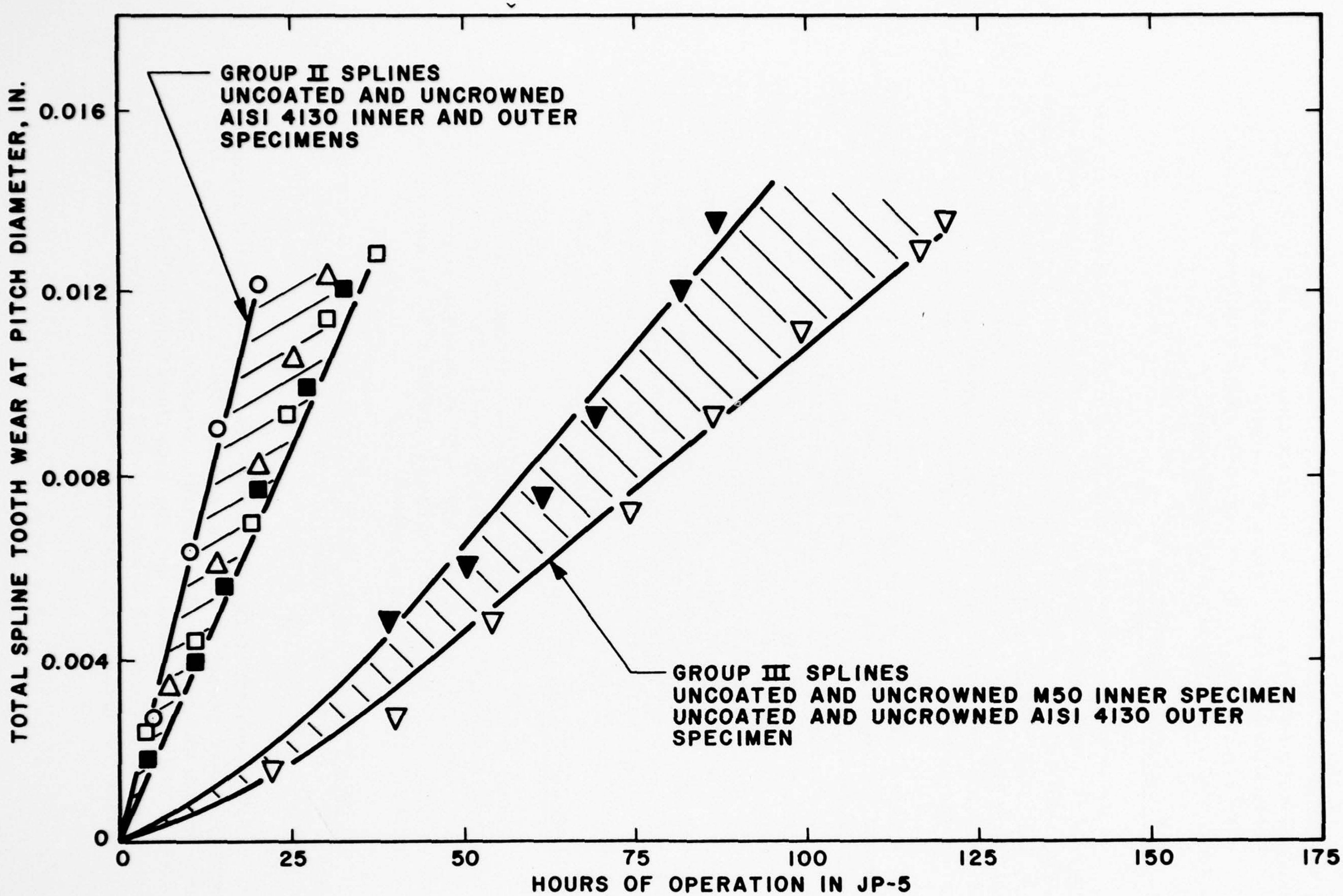


FIGURE A-15. INFLUENCE OF SPLINE MATERIALS ON SPLINE WEAR RATES FOR SPLINES IN JP-5 FUEL (GROUPS II AND III SPLINES)

TABLE A-6. EFFECT OF PLASTIC COATINGS
IN DRY AIR ENVIRONMENT
(Type 2B Splines)

Coating	Induction Period, hr. No Grease	Grease I	Grease B
None	0	2	23
Teflon-S	0	2	29
Nylon-11	0	46	48

Coating	Total Wear at 5 hr, in. No Grease	Grease I	Grease B
None	0.011	0.006	0.001
Teflon-S	0.011	0.006	0.001
Nylon-11	0.007	0.007	0.007

to the very thin Teflon-S coating (1.4 mils) present at the wear site, so that little benefit was derived from it and the behavior was essentially that of the uncoated splines.

Grease I gave an induction period of 2 hours with uncoated splines in dry air. When Teflon-S coated splines were substituted, the induction period was also 2 hours. Use of Nylon-11 coated splines gave, however, an induction period of 46 hours. The wear rate after the induction period was essentially constant in all cases. The total wear at the end of 5 hours was 0.006 inch for both uncoated and Teflon-S coated splines, and 0.007 inch for the Nylon-11 coated splines. Here again, the similarity in performance of uncoated and Teflon-S coated splines was due apparently to the very thin Teflon-S coating present, so that the effect was essentially that of the substrate metal.

In dry air environment, Grease B gave an induction period of 23 hours with uncoated splines, 29 hours with Teflon-S coated splines, and 48 hours with Nylon-11 coated splines. In all cases, the wear was again linear after the induction period. The total wear at the end of 5 hours was 0.001 inch for uncoated and Teflon-S coated splines, and 0.007 inch for Nylon-11 coated splines. Two points are noteworthy here: First, the behavior of uncoated and Teflon-S coated splines was again similar, reflecting mostly the effect of the substrate metal. Second, the behavior of both greases was similar when a thick Nylon-11 coating (10 mils) was used, so that the effect of the substrate metal was essentially absent. The induction period was apparently caused in both cases by the wearing of the nylon material from the male specimen which was smeared over the female specimen; the interaction of the grease and the substrate metal was therefore largely absent.

JP-5 Fuel Environment. In all instances, no induction period was observed in fuel. In the absence of an induction period, the performance can only be compared on the basis of wear. Table A-7 presents the data on total wear obtained at the end of 5 and 25 hours.

Comparison of the 5-hour wear data in Tables A-6 and A-7 indicates that with both uncoated and Teflon-S coated splines, operation in fuel gave a significant reduction in wear without grease and with Grease I. Their similarity in performance again suggests essentially the effect of the substrate metal. On the other hand, at the end of 5 hours, the Nylon-11 coated splines were only partially worn away in dry air and completely worn away in JP-5 with either grease. This indicates that the grease was apparently dissolved and washed away from the wear site by the fuel, so that what little protection that the grease furnished in air was now obliterated.

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A CRITICAL SURVEY AND ANALYSIS OF AIRCRAFT SPLINE FAILURES.(U)
AUG 71 M L VALTIERRA, R D BROWN, P M KU N00156-70-C-2156

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TABLE A-7. EFFECT OF PLASTIC COATINGS
IN JP-5 FUEL ENVIRONMENT
(Type 2B Splines)

Coating	Induction Period, hr		
	No Grease	Grease I	Grease B
None	0	—	—
Teflon-S	—	0	0
Nylon-11	—	0	0

Coating	Total Wear at 5 hr, in.		
	No Grease	Grease I	Grease B
None	0.001	—	—
Teflon-S	—	0.001	0.001
Nylon-11	—	0.011	0.009

Coating	Total Wear at 25 hr, in.		
	No Grease	Grease I	Grease B
None	0.005	—	—
Teflon-S	—	0.005	0.005
Nylon-11	—	0.021	0.017

The total wear at the end of 25 hours followed the same general trends as at the end of 5 hours. As noted previously, the fuel generally provides some lubrication and wear protection, hence it is possible to operate the splines over a more extended period than in dry air.

Comments. The above results show that the thin Teflon-S coating offered no beneficial effect in dry air, and no beneficial effect in JP-5 fuel except when Grease I was used in conjunction with it. The Nylon-11 coating gave substantial beneficial effect in dry air in lengthening the induction period at the sacrifice of the wear of the coating itself, but no beneficial effect in fuel when the induction period was absent.

One of the problems with this investigation was the unequal thicknesses of the plastic coatings used, which were limited by the coating application techniques. The Teflon-S coating might, it is believed, show up better if a greater thickness were employed.

Another problem encountered was the peeling off of the Nylon-11 coating during the wear process, thereby introducing the possibility of metal oxide contamination. Whether this was due to poor bonding of the coating upon the metal substrate, or the excessive thickness of the coating used, is not known. However, it was felt that a thinner Nylon-11 coating, applied with best precaution taken to ensure good bonding, would be well worth trying. This was done by subsequent work at NADC and Kelley AFB, as reported below.

Recent Work by NADC. Work has recently been performed by Naval Air Development Center in an effort to develop techniques for applying thinner coats of Nylon-11. The conventional method of applying Nylon-11 is by a fluid-bed process. This method is limited to a minimum film thickness of 10 mils. Engineers at the Aeronautical Materials Laboratory at NADC have been successful in the development of an electrostatic spraying technique for applying Nylon-11 coatings. It was reported that coating thicknesses of 3 to 4 mils are possible by utilizing this technique. Films are reportedly tougher than the conventional fluid-bed Nylon-11 films applied on the splines used in the SwRI work. The tough 3 to 4 mil film should prove to be better than the fluid-bed Nylon-11 film used in the SwRI work.

Recent work by Kelly AFB. Engineers at Kelly have recently experimented with Nylon-11 coating on generator splines used on the T-38 aircraft. Serious spline wear was experienced after 400 hours of either aircraft or test stand operation (see Appendix E, Item 9a). Limited work at Kelly has been performed utilizing a test stand incorporating a generator

(see T.O. 16G1-102-2) to evaluate the NADC applied Nylon-11 coated spline. An oil mist lubrication was used in conjunction with the Nylon-11 coated spline.

The life of the spline connection was extended from 400 to 1400 hours by the combination of the oil and Nylon-11 coating. After 1400 hours the coating was still intact and had not worn enough to expose the spline teeth. In addition, the generator vibration was less on the Nylon coated spline test.

17. Effect of Metallic Coatings

Figure A-16 illustrates the performance summary of the Group III coated M50 inner specimens (male splines) with AISI 4130 outer specimens (female splines) operating in JP-5 fuel. As noted from the figure, the silver and X (proprietary) coatings gave essentially no wear protection. On the other hand, the Electroless Nickel I, Electroless Nickel II, and Y (proprietary) coatings gave superior performance. This is especially true with the Electroless Nickel II coating, which gave approximately 1000 hours of operating life in fuel.

Further work was carried out in JP-5 fuel environment with the Group XIII splines, which comprised M50 male specimens having a 14.5-in. crown radius coated with Electroless Nickel II and uncrowned and uncoated AISI 4130 female specimens. Although four such sets were made, only one test was performed. At the end of 1000 hours of operation, the total spline wear was only 0.0013 inch, as shown in Figure A-16.

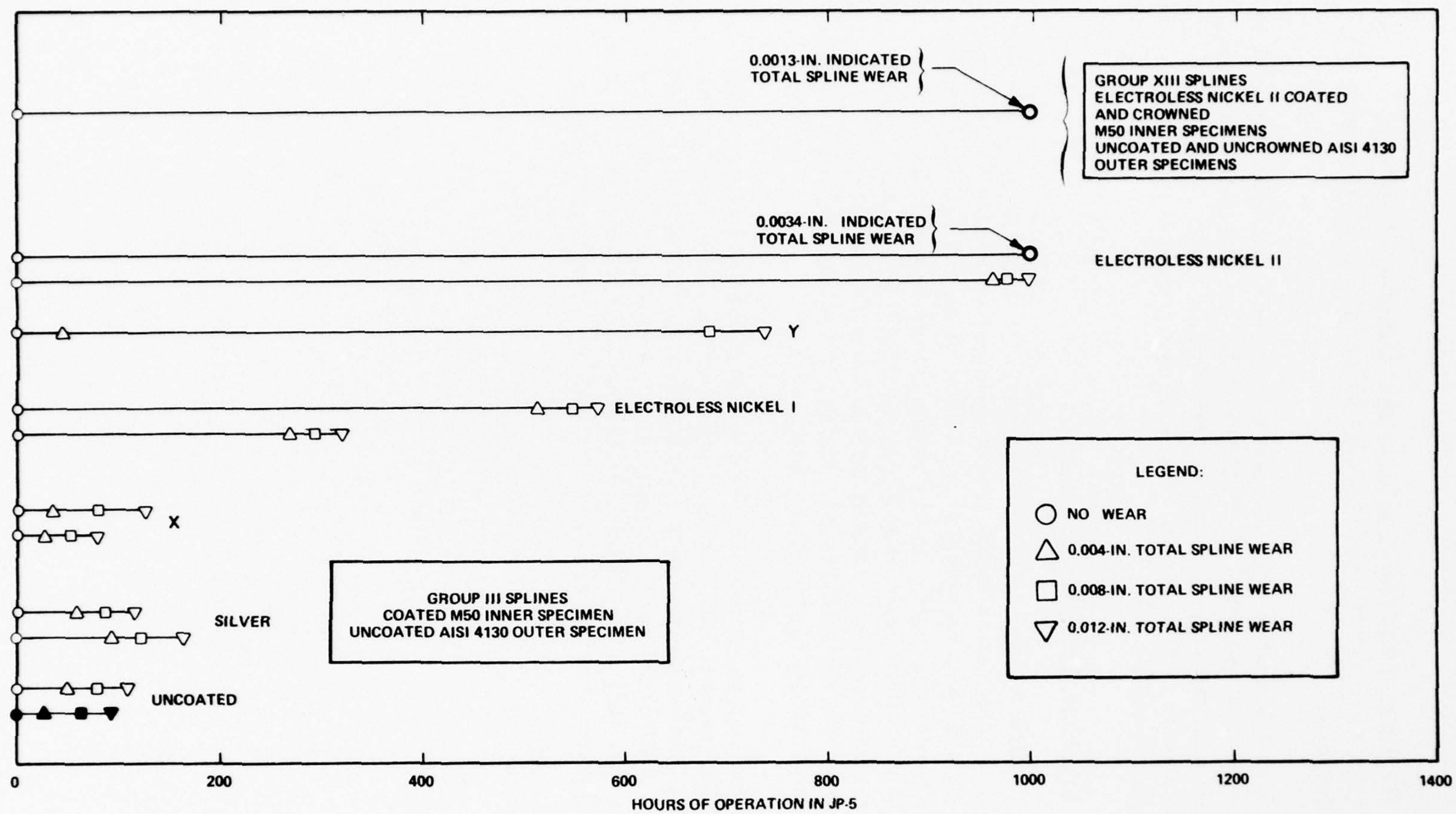

FIGURE A-16. EFFECT OF VARIOUS METALLIC COATINGS AND CROWNED SPLINES IN JP-5 FUEL (GROUPS III AND XIII SPLINES)

APPENDIX B

SUMMARY OF AIRCRAFT SPLINE SURVEY RESULTS

		Page
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Brand names are cited as reported. They do not imply endorsement or otherwise by the authors.

TABLE B-1. SPLINE PROBLEM AREAS REPORTED BY NA

FORM	LOCATION	EQUIPMENT		OPERATING CONDITIONS			MALE SPLINES										Pr
		Aircraft	Engine	Speed Range, rpm	Tooth Load, psi	Temp, °F	Problem Area	Manufacturer	Part Number Accessory	Part Number Spline	Replacement Rate, %	Material	Core Hardness, R_c	Case Hardness, R_c	Case Thickness, in.	Roughness, μin. rms	
207	Alameda	A-4, -E, -F	J-65	2300-8560	180	250	CSD	Lycoming	209769	209880	80	AMS 2485	34-40	62-72	0.009-0.015	32AA	Gearbo
208	"	E-2,C-2	T-56	90°	Unk.	-60 amb	Propeller	Allison	6849145	6851809	1	AMS 6470	33 min.	60	0.010-0.015	125	Propel
209	"	P-3	T-56	14,239	3950	275	(Starter)	AiResearch	100-294	363764	75	AISI 4340		48-56	0.010-0.040	63	Gearbo
212	"	P-3*	T-56	42,000	1360		Turbine	AiResearch	GTCP 95-2	696161-13	10	AMS 4928		50-53		63	Compr
213	"	A-4,A-6	J-52	580-3850	6400	150	Fuel pump	Pesco	023830	02-13756	20	PM 6046				150	(Inside
218	Cherry Pt.	OV-10A	T-76	4000	7450	250	Fuel pump	AiResearch	868511	868484-1	75	M-50		60-65		63	(Inside
219	"	OV-10A	T-76		6370		(Gearbox)	AiResearch		869911	52	AISI-H-11		50-53	0.005-0.010	63	(Fuel
220	"	H-46	T-58			140	Generator										Trans
221	"	F-8*	J-57	8000	390	200	Generator	Bendix	28E10-9D								Air tu
222	"	OV-10A	T-76	3900		150	Fuel pump	TRW	364800-1	209517	86						Gearbo
223	"	CH-46*	T-62	8000	1180	150	Alternator	Solar									Gearbo
224	"	*		5000			Fuel control	AiResearch	GTCP100-54	372086-3	70						Gearbo
170	Jacksonville	A-4	J-52	2300-8560	145		CSD	Lycoming	LD6-10A	209880	80	AMS 2485	34-40	57-62	0.009-0.015	32	Gearb
171	"	A-4,A-6	J-52	580-3850		150	Fuel pump	Pesco	023830-060	012-13580	70	Nitriding St				150	(Inside
172	"	A-5	J-79	3686		250	Hyd. pump	N. Y. Air Brake	51054	51762	55	AMS 5648D	40-45				Gearbo
173	"	A-4E	J-52	3200-4000			Starter			648865							Gearbo
189	"	A-4 several	J-52	11,000-12,000		250	Engine	Pratt & Whitney	Hub	500407		AMS 4928T1					Eng. le
174	"	A-4B, -C	J-65	3000-4000			(Hyd. pump)	Vickers	AA65315-R6	103488							Gearbo
176	Norfolk	P-3A,C-130	T-56			180	Alternator	Bendix	6825800	1532300	50**	E-4350-1	34-48	48-52	0.3125		Gearbo
177	"	P-3A,C-130	T-56	0-8500		180	Air starter	Allison	6825800	2481939							Gearbo
178	"	A-6	J-52	3000-10,000	360	250	CSDS	AiResearch	100-10	359632	20	AISI 4340		50-54			Gearbo
202	N. Island	H-2C	T-58			150	Hyd. pump	N. Y. Air Brake									Gearb
203	"	S-2, -E1	R-1820	2300-9025			(CSD)	Sundstrand	692187	825093	60	AMS 6260E	30-41	57-62	0.015-0.025		Gearb
204	"	S-2, -E1	R-1820		1620	160	(CSD)	Sundstrand	117P10010	824240	60	AMS 6415E		40-45			Shaft
205	"	H-46	T-58				Starter	N. Y. Air Brake		5130	25	AMS 6260E	N/A				Gearb
206	"	H-2C	T-58	8238		150	Generator	Bendix		1109357							Gearb
225	"	F-4	J-79		1480		CSD	G. E.	7037E44C-7	538D946P1	50	B50TA-317B1	23-29	45-55		125	Gearb
226	"	H-2C	T-58	4080			Fuel pump	Pesco									Gearb
228	"	H-2C	T-58	6000		-65 to 275	(Starter)	N. Y. Air Brake		5130							Gearb
229	"	H-2C	T-58	4080		-65 to 110	Fuel pump	Pesco	023104	02-13621	90						(Insid
230	"	H-2C	T-58	4080		-65 to 110	Fuel pump	Pesco	023104-25	02-14066	35	PM6003	N/A		DS-17		(Insid
231	"	F-4	J-79	7685	325	300 to 350	Scav. oil pump	Lear-Siegler		RB 16727	100	Nitralloy 135					Turb
232	"	F-4	J-79	3800	275	250 to 300	Fuel pump	Pesco	024090-019/021	02-13407	20	PM6007			DS-16		Gear
239	"	H-53		13,600			Engine	G. E.		5012T41G01		AMS 6415	40-46	46 min	0.010-0.030	32	
240	"	H-53		4540	1000		Hyd. pump			5869		AISI 3310					Gear
241	"	H-3	T-58	3710	600		Hyd. pump	Sikorsky	S6135-21000	S6135-20763-1	40	AISI 9310	30-40	58-64	0.010-0.025	100	Main
242	"	H-3	T-58	3740	960		Hyd. pump	N. Y. Air Brake		67A1502-1		AISI 3310					Main
243	"	H-3	T-58				Generator	Bendix	28B135-29-A/K	1531453							Main
244	"	H-3	T-58	3710	960		Hyd. & oil pump	N. Y. Air Brake		67A1502-1		AISI 3310					Main
117	Pensacola	T-2	J-60, J-85	3860-5800			(Hyd. pump)	Vickers	AA65306R6	103488	10						Gear
118	"	T-2A	J-34	2700-8000			Generator	Bendix	30BH3-3A	1105068	20						Gear
122	"	F-9	J-48	950			Starter	Jack & Heintz	D3150ZA	20031-1025	40						Gear
123	"	S-2	R-1820	1500-3000			Hyd. pump	N. Y. Air Brake	66DWB-300-6	2208	90						Gear
124	"	T-28	R-1820	3000-8000			Generator	Jack & Heintz	G300-4B	G300-367	15	AISI 6150					Gear
127	"	T-28	R-1820	3000-8000			Generator	G. E.	2CM70-D2	9411984G01	25						Gear
128	"	T-28	R-1820-86	3000-8000			Generator	G. E.	2CM70DGA	128B831G1	25						Gear
180	Quonset Pt.	RB-66	J-71	3000-4000		130	(Hyd. pump)	N. Y. Air Brake	66WU300-2	67B1503	60	QQ570					Oil p
181	"	RB-66	J-71	3000-4000		130	Oil pump	Allison	6802000	67B1503	60	QQ570					Hyd.
182	"	F-4B, -J	J-79		1470	200	CSD	G. E.	7037E44-C-7	538D946P1	<50	B50TA-317B1					Gear
183	"	H-3	T-58			250	(Oil pump)	Sikorsky	S6135-20815-2	S6135-20763-2	8	AISI 9310	30-40	58-64	0.010-0.025		Gear
184	"	H-3	T-58			250	(Hyd. pump)	N. Y. Air Brake	66WAN200	67B-1502-1	50						Oil p
185	"	H-3	T-58	7600-8400		250	Generator	Bendix	28B135-29A/K	1531453-3	50						Gea
186	"	H-3	T-58	3700		300	(Hyd. pump)	N. Y. Air Brake	66WAN-200	67A-1502	50	AISI 3310					Gea
187	"	S-2, -D, -E	R-1820	5500-7000	1620	200	(CSD)	Sundstrand	117P10010	824240	25	AMS 6415E		40-50			Shaf
188	"	S-2, -D, -E	R-1820	4500-5800			(CSD)	Sundstrand	117P10010	825093	15	AMS 6260E	30-41	57-62	0.015-0.025		Gea

Items in parentheses indicate dogbone spline
* APU
** Now lower

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REPORTED BY NAVY ORGANIZATIONS WITH PERTINENT DETAILS

Case Hardness, R_c	Case Thickness, in.	Roughness, µin. rms	FEMALE SPLINES: Problem Area	Manufacturer	Part Number: Accessory	Part Number: Spline	Replacement Rate, %	Material	Core Hardness, R_c	Case Hardness, R_c	Case Thickness, in.	Roughness, µin. rms	LUBRICATION: Lubricant	Lubricant Spec.	Lub. Interval, hr.	FORM
62-72	0.009-0.015	32AA	Gearbox	Wright	AN 4182-2	AN 4182-2							Grease	MIL-G-21164		207
60	0.010-0.015	125	Propeller	Allison	A6441FN-248	6849142	12	AMS 6415	30-37	60	0.010-0.015	100	Grease	MIL-G-25537	60-100	208
48-56	0.010-0.040	63	Gearbox	Allison	6825800	6789329	99	AMS 6260	30	60	0.010-0.025		Grease	MIL-G-81322	600	209
50-53		63	Compressor	AiResearch	GTCP-95-2	379548-50	25	Titanium				63	None	None	-	212
		150	(Inside)fuel pump	Pesco	023830	02-13579	0						JP-4	MIL-T-5624D		213
60-65		63	(Inside)fuel pump	AiResearch	868511	868460	20	BG 42 titanium					JP-4	MIL-T-5624		218
50-53	0.005-0.010	63	(Fuel pump)	AiResearch		868484-1	75	AISI M-50	60-65				Lubriplate 630-AA		Cal. Insp.	219
			Transmission	Boeing Vertol	A02D2012	A02D2290-5	65	AISI 9310	36-42	59-64	0.010-0.030	80		MIL-G-21164		220
			Air turbine drive	Bendix	46E01	642008	20	AMS 6470	36-41	62-78	0.008-0.013	63	Plastilube Moly No. 3		120	221
			Gearbox	TRW	364800-1	211117	56						Solid Film	MIL-L-8937		222
			Gearbox	Solar	T62T11	30411-1	12	AMS 6260			0.010			MIL-L-7808		223
			Gearbox	AiResearch	GTCP-100-54								None	None	-	224
57-62	0.009-0.015	32	Gearbox	Pratt & Whitney		431982	5	AMS 6260	30-40	60-68	0.025-0.040		Grease	MIL-G-21164	450	170
		150	(Inside)fuel pump	Pesco	023830-060-1	02-13756	80	Berrylium cu.				150	JP-4	MIL-T-5624		171
			Gearbox			516D832-P2							Grease	MIL-G-21164	1100	172
			Gearbox	Pratt & Whitney		383266	54	AMS 6260	30-40	60-67	0.025-0.040		Grease	MIL-G-21164	180	173
			Eng. location C	Pratt & Whitney		623354		AMS 6260	30-40	60-67	0.040		Oil	MIL-L-23699		189
			Gearbox			135886									1000	174
48-52	0.3125		Gearbox	Allison	6825800	6825238	75	AMS 6260	30	60	0.010-0.025		Grease	MIL-G-21164	4000	176
			Gearbox	Allison	6825800	6789329	100	AMS 6260	30	60	0.010-0.025				3000	177
50-54			Gearbox	AiResearch	CSDS100-10	383266		AMS 6260	30-40	60-67	0.025-0.040					178
			Gearbox	Kaman	K674702	K674733-13	100	AMS 6471	38-45	64	0.005-0.008	125				202
57-62	0.015-0.025		Gearbox	Pratt & Whitney			75			58-62			Plastilube Moly No. 3			203
40-45			Shaft power	Bendix	117P10010	646617	75	AMS 6260	36				Plastilube Moly No. 3		150	204
			Gearbox													205
			Gearbox	Kaman	K674702	K674732-13	100	AMS 6471	38-45	64	0.005-0.008	125	Grease	MIL-G-21164		206
45-55		125	Gearbox	G. E.		516D839P1	22			50	0.010-0.025	63	Plastilube Moly No. 3	FSN 9150-889-3516		225
			Gearbox	G. E.	37E500250G008	4000T45P02	13	AMS 6265	32-42	58-63	0.010-0.025	125	Plastilube Moly No. 3	FSN 9150-889-3516		226
			Gearbox	G. E.	37C300353G011	37D400428P102	39	AMS 6260	32-42	58-63	0.010-0.025	125	Plastilube Moly No. 3	FSN 9150-889-3516		228
			(Inside)fuel pump	Pesco	G23104-All	02-14418	95	AMS 6475		DS-17		DS-5	JP-4	MIL-T-5624		229
	DS-17		(Inside)fuel pump	Pesco	023104-25	02-13078	5						JP-4	MIL-T-5624		230
			Turbine baffle	G. E.		514D318G1/G3/P6	15					63	Molydisulfide	MIL-L-25681B		231
	DS-16		Gearbox	G. E.	109R429	516D109P2	0					125	Plastilube	FSN 9150-889-3516		232
46 min	0.010-0.030	32		Sikorsky	65355-12000	65355-12033-102	23	AISI 9310	30-45	58-64	0.025-0.040	90	Grease	MIL-G-3545		239
			Gearbox	Sikorsky	65356-04000	65356-04030-101	19		30-45	58-64	0.020-0.030	90	Grease	MIL-G-21164		240
58-64	0.010-0.025	100	Main gearbox	Sikorsky	S6135-21000	S6135-20070-2	76	AISI 9310	30-40	58-64	0.010-0.025	100	Grease	MIL-G-21164		241
			Main gearbox	Sikorsky	S6135-21000	S6135-20181-2	34	AISI 9310	30-40	58-64	0.010-0.025	100	Grease	MIL-G-21164		242
			Main gearbox	Sikorsky	S6135-21000	S6135-20756-3	79	AISI 9310	30-40	58-64	0.010-0.025	100				243
			Main gearbox	Sikorsky	S6135-21000	S6135-20763-1	40	AISI 9310	30-40	58-64	0.010-0.025	100	Grease	MIL-G-21164		244
			Gearbox				20						Grease	MIL-G-21164	OH	117
			Gearbox	Westinghouse		107T851	50	AMS 6260	32-42	58-63	0.015-0.025		Plastilube Moly No. 3	MIL-L-3545	1000	118
			Gearbox	Pratt & Whitney		187270	N/A						Grease	JH 13555	Eng. time	122
			Gearbox	N. Y. Air Brake	66DWB-300-6	67B1156	N/A	M-2	50-53	58-60			Grease	MIL-G-21164	OH	123
			Gearbox										Grease	MIL-G-3545	1000	124
			Gearbox												1000	127
			Gearbox	Wright		120363	20	AMS 6260	32-40	51-63	0.015-0.025	130	Plastilube Moly No. 3 &	MIL-G-3545B	1000	128
			Oil pump	Allison	6802000	6747679	50	AMS 6260	30	60	0.015-0.025		Plastilube Moly No. 3	FSN 9150-823-8045	500	180
			Hyd. pump	N. Y. Air Brake	66W	67B1156	60	M-2-HS	50-53	58-60			Plastilube Moly No. 3 or	MIL-G-21164A	800	181
			Gearbox	G. E.	107R894	311D544	30			50	0.010-0.025	63	Plastilube Moly No. 3	FSN 9150-889-3516	800	182
58-64	0.010-0.025		Gearbox	Sikorsky	S6135-21000	S6135-20070-2	80	AISI 9310	30-40	58-64	0.010-0.025		MIL-G-21164 or	MIL-G-7187	750	183
			Oil pump	Sikorsky	S6135-20815-2	S6135-20763-2	80	AISI 9310	30-40	58-64	0.010-0.025		MIL-G-21164 or	MIL-G-7187	1000	184
			Gearbox	Sikorsky	S6135-21000	S6135-20756-3	50	AISI 9310	30-40	58-64	0.010-0.025		MIL-G-21164 or	MIL-G-7187	750	185
			Gearbox	N. Y. Air Brake	66WAN200	3444	50	QQ-T-590	58-60				Plastilube Moly No. 3 or	MIL-G-7187 or -21164	1000	186
40-50			Shaft power	Bendix	117P10010	646617	20	AMS 6260	36	36	0.015-0.020		Plastilube Moly No. 3 or	Pioneer 31	120	187
57-62	0.015-0.025		Gearbox	Sundstrand	117P10010	824939	20	AMS 6263		58-62	0.022-0.038		Plastilube Moly No. 3 or	Piineer 31	120	188

TABLE B-2. SPLINE PROBLEM AREAS REPORTED BY OTH

FORM	LOCATION	EQUIPMENT		OPERATING CONDITIONS			MALE SPLINE									
		Aircraft	Engine	Speed Range, rpm	Tooth Load, psi	Temp °F	Problem Area	Manufacturer	Part Number Accessory	Part Number Spline	Replacement Rate, %	Material	Core Hardness R_c	Case Hardness R_c	Case Thickness, R_c	Roughness, μin. rms
245	Kelly	T-38	J-85	0-7811			(Gearbox) D. B.	Bendix	19E83-2ACL-52	2481790	45	E-4350				
91	"	F-84F	J-65WD	0-3670	3080		(Fuel pump)	Pesco		02-353	100	Nitralloy N		60 min.		60
96	"	*B-52H*	*TF-33P3*	*7600-8400*	*750*		*(Generator)*	*Westinghouse*	976J006-9	958C778	20	*AISI 4140*	48-52			
97	"	C-123K	R-2800	4500-8000			(Generator)	G. E.	2CM73E4	36B506282-AAG1		AMS 6260				
99	"	T-38	J-85				(Generator)	Westinghouse		956C134	100	PDS10306CG				64
112	"	T-38	J-85	0-7811	3400		(Engine)	Bendix	19E83-2ACL-51	2481789		E 4350	38-42			
233	"	T-38	J-85	24,000			(Fuel pump)	Chandler-Evans	923487	22255	56					
234	"	C-5	TF-39				Engine internal	G. E.	TF-39	9634M92P01						50
235	"	C-5	TF-39				Engine internal	G. E.	TF-39							63
236	"	T-38	J-85				(Shaft power)D. B.	Bendix		2481789		E 4350-1	38-42			63
237	"	T-38	J-85	0-7811			(Shaft power)D. B.	Bendix	19E83-2ACL-52	2481790	45	E 4350-1	38-42			63
238	"	T-38	J-85	0-7811			Fuel pump	Chandler-Evans	923487	22255	56					
193	Tinker	HH-53	T-64	4543		250	(Hyd. pump)	N. Y. Air Brake	65WB02003	4156-1		AMS 6260				
194	"	RC-135C;B-52H	TF33-P9-P3	4475-7980	13850	350	(CSD)	Sundstrand	706822	707002	17	AMS 6415	35 min.	50-55		
195	"	*RC-135C;B-52H*	*TF33-P9-P3*	*4475-7980*	*13850*	*350*	*(CSD)*	*Sundstrand*	706822	707002	17	AMS 6415	35 min.	50-55		
196	"	F-4	J-79	4750-7685	1500	225	(Inside CSD)	Sundstrand	695145C	697157	20	AMS 6260	35-42	58-63	0.015-0.030	
197	"	F-4	J-79	0-3050			(Starter)	AiResearch	383242-1-7	361825-2		SAF 4340	35-38			63
198	"	F-4	J-79	4750-7685	690	225	(CSD)	Sundstrand	695145C	697157	85	AMS 6260	35-42	58-63	0.015-0.030	
199	"	KC-135,B-52	J-57	3260	910		Fuel pump	Pesco	022994	02-13738	59	AISI 4140	45-50			
200	"	KC-135	J-57	3260			Inside fuel pump	Pesco	022994	02-13924	74					
129	ARADMAC	UH-1C, H	T-53	4400-8000	185		Starter generator	Lear-Siegler	23064-001	23064-1011	48					
132	"	UH-1 B, C, F	T-53	4400-8100	205		Starter generator	Bendix	VG 700	VG 1117	7	AMS 6415	42-46			
133	"	UH-1 B, C, D	T-53	4400-9000	115		Starter generator	Lear-Siegler	23031-004	23014-1055	48					
134	"	UH-1	T-53	4500-6500			Generator	Jack & Heintz	*30010-000*	59SAB16305	48					
135	"	UH-1B thru F	T-53	294-324	10690		Main rotor mast	Bell Helicopter		204-011-450	50	AISI 4340				
136	"	CH-47	T-55	6950-7550	2830		Eng. shaft trans.	Boeing Vertol	11D6001-6, 7, 8	114D6045	10	AISI 9310		60-64	0.008-0.020	
137	"	*CH-47*	*T-55*		*3540*		*Drive shaft cplg.*	Boeing Vertol		114D3205	5	AISI 4340	58	60-64		
142	"	UH-1A thru D	T-53	1600	2560		90° shaft	Bell Helicopter	204-040-004-25	204-040-402	20	AISI 4620		60-63	0.010-0.020	32
144	"	UH-1	T-53	6000-6600	1350		Eng. shaft trans.	Bell Helicopter	204-040-010-7	204-040-687	40	AMS 6260	38-44	65	0.018	32
145	"	UH-1	T-53		10990		Eng. trans. 42°	Bell Helicopter		204-040-603-5	15	AMS 6260	30-40	60-63	0.015-0.025	
146	"	UH-1B thru F	T-53	294-324	5455		Main rotor mast	Bell Helicopter	Spline C	204-011-450	50	AISI 4340				125
147	"	UH-1C, E	T-53	294-324	12730		Main rotor mast	Bell Helicopter	Spline B	204-011-450	50	AISI 4340				125
214	United	DC-8	JT-4-3	8000	460	200	Generator	Lear-Siegler								
160	AiResearch	727*	GTCP-85	40,000	4840	300	(Compressor)	AiResearch	380049	379539	100	AISI 4340		50-54		
161	"	Lear Jet*	T-76	4000	12900	250	Fuel pump	AiResearch	868511	868484-1	100	M-50		60-65		
162	"	F-27, -28*	GTP-30	60,000	5300	300	(Drive)	AiResearch	GTP 30	379953	100	MS 4340		50-54		63

TABLE B-3. TROUBLE-FREE SPLINE CONNECTIONS RE

210	Alameda	P-3	T-56	6000	820	275	Alternator	Bendix	28B95-15A	1532300	50**	E 4350-1	34-38	48-52	0.03125	
201	Amer. Air	707, 727	JT-3D, -8D	2200-3600	570	300 to 450	Hyd. pump	Vickers	AS66651-L8A	316844		Berrylium Cu.				
108	*Bendix*	*CF-5*	*J-85*	*0-7811*	*5480*	350	*Hyd. pump*	Bendix	34E94-5C	2482788		MIL-S-6709	34-38	91-94.5	0.003-0.009	64
110	Bendix	CF-5	J-85	3300-9000	4018		Shaft power	Bendix		2483590(Z)		E 4350	38-42	48-54	0.030 min.	
227	N. Island	F-8	J-57				Fuel pump	Pesco	022935	02-14013	60**	PM 6003				
215	United	727, 737	JT-8D	7400	12445	400										
216	United	727, 737	JT-8D	6500-11400	16800	400										32

Items in parentheses indicate dogbone spline

* *APU*

** Now lower

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PORTED BY OTHER ORGANIZATIONS WITH PERTINENT DETAILS

Core Hardness, R_c	Case Hardness R_c	Case Thickness, R_c	Roughness, μin. rms	FEMALE SPLINE: Problem Area	Manufacturer	Part Number: Accessory	Part Number: Spline	Replacement Rate, %	Material	Core Hardness, R_c	Case Hardness, R_c	Case Thickness, in.	Roughness, μin. rms	LUBRICATION: Lubricant	Lubricant Spec.	Lub. Interval, hr.	FORM
				Shaft power cplg.	Bendix	19E83-2ACL-52	2481791		AMS 6260	36		0.015		Plastilube Moly No. 3 or	MIL-G-23827	400	245
	60 min.		60	Gearbox	Wright		229877	100	AMS 6260	32-40	51-63	0.015-0.025	60				91
8-52				(Inside) generator	Westinghouse	976J006-9	958C859-1	15	4140	38-43			63	Grease	MIL-G-3545		96
				Gearbox	Pratt & Whitney		164283	14						Grease	MIL-G-21164		97
			64	Gearbox	Northrup		3-51155	87	4620	32-40	56	0.010-0.020	63	Grease	MIL-G-25537	400	99
8-42				Shaft power cplg.	Bendix	19E83-2ACL-51	2481791		AMS 6260	36 min.	60	0.010-0.015		Plastilube Moly No. 3	MIL-G-23827	400	112
				Gearbox			23066	35						Plastilube Moly No. 3		800	233
			50	Eng. internal	G. E.	TF-39	9661M85				50-55			Oil	MIL-L-7808		234
			63	Eng. internal	G. E.	TF-39	9609M89P02						63	Oil	MIL-L-7808		235
8-42			63	Engine	G. E.		37E501316	50		32-42	58-63	0.030	63	Grease	MIL-G-23827	400	236
8-42			63	Gearbox	Northrup		3-51232-501		4620				32	Grease	MIL-G-23827	400	237
				Gearbox	G. E.		D401204P103	34						Plastilube Moly No. 3		800	238
				(Gearbox)	N. Y. Air Brake	65WB02003	4153		QQT-590		58-60						193
5 min.	50-55			Inside CSD	Sundstrand	706822	707811	15	AMS 6260	35-42	58-62	0.022-0.040		688272	Sundstrand		194
5 min.	50-55			Gearbox	Pratt & Whitney		596011	12	AMS 6260	30-40	60-67	0.025-0.040		688272	Sundstrand		195
5-42	58-63	0.015-0.030		(Inside) CSD	Sundstrand	695145C	697155-1							Molykote G		600	196
5-38			63	Gearbox	AiResearch	383242-1-7	360295		AMS 6415				63	Pioneer 31	Bendix		197
5-42	58-63	0.015-0.030		Gearbox	G. E.		875C106				50	0.010-0.025		Molykote G		600	198
5-50				Gearbox	Pratt & Whitney	276900	522058	50	AMS 6260	30-40	60-67	0.025-0.040					199
				(Inside)fuel pump	Pesco	022994	02-13740	59						JP-4	MIL-T-5624		200
				Gearbox	Lycoming		1-080-310-01	40			58-63	0.010-0.030		Pioneer 31 or	MIL-G-3545		129
42-46				Gearbox	Bell Helicopter		204-040-102-13	12	AMS 6260	33-41	60	0.010-0.020					132
				Gearbox	Lycoming		1-080-310-01	40			58-63	0.010-0.030					133
				Gearbox	Bell Helicopter		205-040-103-1							Grease	MIL-G-3545		134
				Spline A	Bell Helicopter	Main rotor mast	204-011-105	5	AISI 4340					Corrosion	MIL-C-11796	1100	135
	60-64	0.008-0.020		Shaft eng. trans.	Boeing Vertol	11D6001-6, -7, -8	114D6044-10	60	AISI 9310	36-40	60-64	0.008-0.022		Oil	MIL-L-23699		136
58	60-64			Eng. trans.	Boeing Vertol	11D6001-6-16	114D6065	50	AISI 9310	58	60-64			Oil	MIL-L-23699		137
	60-63	0.010-0.020	32	Tail rotor spline	Bell Helicopter	204-040-004-25	204-010-720-3		AISI 4140					Solid Film	MIL-L-46010		142
38-44	65	0.018	32	Cplg. main drive	Bell Helicopter	204-040-010-7	204-040-688	80	AMS 6470	32-46	60	0.013	32	Anderol L-786			144
30-40	60-63	0.015-0.025		Gearbox	Bell Helicopter		204-040-604-5	15	AMS 6260	30-40	60-63	0.015-0.025		Anderol L-786			145
			125	Spline C	Bell Helicopter	Main rotor mast	204-010-479	5	4640				63	Grease	MIL-G-25537	100	146
			125	Spline B	Bell Helicopter	Main rotor mast	540-011-486	12	Al bronze				63	Corrosion	MIL-C-11796	1100	147
				CSD front comp.					AISI 52100	58-62	58-62			688272	Sundstrand	1500	214
	50-54			Compressor	AiResearch	380049	696161	50	Titanium				63	Oil vapor	MIL-L-23699/7808		160
	60-65			Internal fuel pump	AiResearch	868511	868460		BG 42					JP-4	MIL-T-5624		161
	50-54		63	Gas turbine	AiResearch	GTP 30	694877		EMS 4340	34-48			63	Oil vapor	MIL-L-23699/7808		162

CONNECTIONS REPORTED BY NAVY AND OTHER ORGANIZATIONS

34-38	48-52	0.03125		Gearbox	Allison	6825800	6825238	90	AMS 6260	30 min.	60	0.010-0.025		Grease	MIL-G-21164		210
				Gearbox	Pratt & Whitney		385375		AMS 6260	30-40	60-67	0.025-0.040		Grease	Molykote 343X	1500	201
34-38	91-94.5	0.003-0.009	64	Gearbox	G. E.		6005T95		AMS 6470	32-36	91 min.	0.005-0.008		Grease	Plastilube Moly No. 3	400	108
38-42	48-54	0.030 min.		Shaft power	Bendix	19E83-4ACL60	2481791		AMS 6260	36 min.		0.010-0.015		Grease	MIL-G-23827		110
				Gearbox	Pratt & Whitney		450849	60**	AMS 6260	30-40	81-85	0.025-0.040	32				227
				Hub					AMS 4928					Graphite varnish		16,000	215
			32	Assembly drive					AMS 6304					Oil	MIL-L-23699		216

TABLE B-4. SPLINE HISTORY, WEAR MEASUREMENT AND REJECTION CRITI

FORM	LOCATION	EQUIPMENT		SPLINE HISTORY, hrs.						SPLINE WEAR MEASUREMENT																			REJECTION				
				MALE			FEMALE																										
		Aircraft	Engine	Accessory OH	Spline OH	Spline Life	Gearbox OH	Spline OH	Spline Life	Backlash	Ball, Dial-indicator	Comparator, Optical	Comparator, Pocket	Depth Gage	Door-Knob	Feeler Gage	Go-No-Go	Micrometer	Pins or Wires	Photographs	P & W Tools	Shadowgraph	Stylus	Versa-Dial	Versa-Dial w/Q. P. Tip*	Vinco Gage	Visual	Not Specified	Few Thousandths, Inch	10% of Tooth Land	20% of Tooth Land	33% of Tooth Land	50% of Tooth Land
207	Alameda	A-4E, -F	J-65	1000		300						M																	M				
208	"	E-2, C-2	T-56	2200	2200		2200	2200				M		F															MF				
209	"	P-3	T-56	1200*			4500	4500																			MF		F	M			
212	"	P-3	T-56	3000	3000		3000	3000																			MF		MF				
213	"	A-4, A-6	J-52	1500	1500		1500	1500				MF																	MF				
218	Cherry Pt.	OV-10A	T-76									M																	MF				
219	"	OV-10A	T-76																														
220	"	H-46	T-58	600	600				1200													F											
221	"	F-8	J-57	500		1000			1000																		F						
222	"	OV-10A	T-76	1600		1400			1400										MF										MF				
223	"	CH-46	T-62	3000*			3000*																				F						
224	"			2000*																													
170	Jacksonville	A-4	J-52	1000	120						M																		M				
171	"	A-4, A-6	J-52																MF										MF				
172	"	A-5	J-79	1000	1000																												
173	"	A-4E, -F	J-52	1000																													
189	"	A-4 several	J-52		2000														MF										MF				
174	"	A-4B, -C	J-65	1000	1000		1000	1000																									
176	Norfolk	P-3A, C-130	T-56		2000		5000	4000																									
177	"	P-3A, C-130	T-56				5000	3000																									
178	"	A-6	J-52				720	3600																									
202	N. Island	H-2C	T-58	750	500	500			500						F				F								F		F				
203	"	S-2, -E1	R-1820																										M				
204	"	S-2, -E1	R-1820								M																		M				
205	"	H-46	T-58						500																		M						
206	"	H-2C	T-58						500						M				F								M		MF				
225	"	F-4	J-79												F														F				
226	"	H-2C	T-58												F				M										MF				
228	"	H-2C	T-58																										F				
229	"	H-2C	T-58		400-1000			400-1000											M							F	F		MF				
230	"	H-2C	T-58	1800			1800												M										MF				
231	"	F-4	J-79																M										M		F		
232	"	F-4	J-79																MF								M		MF				
239	"	H-53									F								M										MF				
240	"	H-53									F								MF										MF				
241	"	H-3	T-58								MF																		MF				
242	"	H-3	T-58								MF																		MF				
243	"	H-3	T-58																														
244	"	H-3	T-58								MF																		MF				
117	Pensacola	T-2	J-60, J-85	750	750														MF													MF	
118	"	T-2A	J-34	1000															MF										MF				
122	"	F-9	J-48	Eng.life															MF										MF				
123	"	S-2	R-1820														F										M						
124	"	T-28	R-1820	1000															M														
127	"	T-28	R-1820	1000															M														
128	"	T-28	R-1820	1000															M								F		F				
180	Quonset Pt.	RB-66	J-71	800	800	1500	800	800	1500																MF					MF			
181	"	RB-66	J-71	800	800																				MF					MF			
182	"	F-4B, -J	J-79				800	800	1600																								
183	"	H-3	T-58	750	750	600			600																MF				MF				
184	"	H-3	T-58	1000	1000	1500																			MF				F	M			
185	"	H-3	T-58				750	750																	MF				F	M			
186	"	H-3	T-58	1000	1000		1000	1000																	MF				F	M			
187	"	S-2, -D, -E	R-1820	1000	1000		750	750																	MF				MF				
188	"	S-2, -D, -E	R-1820	1000	1000		1000	1000																	MF				MF				

*Hours or number of starts
M=Male
F=Female

ECTION CRITERIA, AND CORRECTIVE RECOMMENDATIONS BY NAVY ORGANIZATIONS

			REJECTION CRITERIA									CORRECTIVE ACTION			CORRECTIVE TECHNIQUES														REMARKS	FORM
	Visual	Not Specified	Few Thousandths, Inch	10% of Tooth Land	20% of Tooth Land	33% of Tooth Land	50% of Tooth Land	90% of Tooth Land	Knife Edge	Individuals Discretion	Not Specified	Current	Proposed	None	Alignment	Crowned Spline	Cut and Replace	Grease	Hardness	Material	Muff	Oil Mist	Plating Repair	Redesign	Research Program	Seal	Surface Treatment	Wet Pad		
			M										M								M								1st ECP No. 33; Spring loaded muff; 2nd AYC No. 292	207
			MF									MF					F							M						208
	MF		F	M									MF															MF	Variety of greases; Allison will propose wet spline.	209
	MF		MF											MF																212
			MF											MF																213
			MF											MF											MF				SwRI Research (see Appendices A and E).	218
												MF						MF											IPPB No. 27: MIL-G-81322.	219
												F							F											220
	F													MF																221
			MF									MF						MF											LES specifies Plastilube Moly No. 3.	222
	F										F			MF																223
												M												M					Entire fuel control is being replaced by a new design.	224
			M										MF								MF								ECP No. 33.	170
			MF									MF							MF				MF						Chrome flash; NAVAIR 03-110DAA-17.	171
																														172
												F											F						Chrome flash.	173
			MF									M					M												Engine in service 10 yrs.; J57 PPC No. 95; cut and pin spline sleeve.	189
																														174
													MF															MF	Allison developed wet spline.	176
																														177
														MF																178
	F		F											MF															Excessive spline wear; does not require measuring tools.	202
			M											MF																203
			M																											204
	M																													205
	M		MF						M					MF																206
			F																											225
			MF											MF																226
			F								M																			228
F	F		MF									MF									MF								PPC No. 85 incorporates muff.	229
			MF																											230
			M		F																									231
	M		MF																											232
			MF																											239
			MF																											240
			MF																											241
			MF																											242
																														243
			MF																											244
						MF								MF															OH Manual NAVAIR 03-30CH-102; IPB NAVAIR 03-30CH-103	117
			MF											MF																118
			MF									MF												MF					LED NA 03-SCA-52/PN 4: Pin measurement, replace dogbone.	122
	M									M				MF															Similar model no problem. Muff and grease retention used.	123
								M						MF															OH Manual NAVAIR 03-30CS-535; IPB NAVAIR 03-30CS-536.	124
								M																					NAVAIR 03-5AD-584; IPB 03-5AD-585.	127
	F		F					M						MF															NAVAIR 03-5AD-584; IPB 03-5AD-585.	128
				MF								F					F												Cut off worn spline and weld in splined insert.	180
				MF									MF								MF								Muff proposed, see T. O. 9HA-2-41-14.	181
												F					F													182
			MF											MF																183
			F	M										MF																184
			F	M										MF																185
			F	M										MF																186
			MF										MF											MF		MF			"O" ring on male; lengthen male spline.	187
			MF											MF																188

TABLE B-5. SPLINE HISTORY, WEAR MEASUREMENT AND REJECTION CRITE

FORM	LOCATION	EQUIPMENT		SPLINE HISTORY, hrs. MALE			FEMALE			SPLINE WEAR MEASUREMENT																			REJECTI			
		Aircraft	Engine	Accessory OH	Spline OH	Spline Life	Gearbox OH	Spline OH	Spline Life	Backlash	Ball, Dial-indicator	Comparator, Optical	Comparator, Pocket	Depth Gage	Door-Knob	Feeler Gage	Go-No-Go	Micrometer	Pins or Wires	Photographs	P & W tools	Shadowgraph	Stylus	Versa-Dial	Versa-Dial w/Q. P. Tips	Vinco Gage	Visual	Not Specified	Few Thousandths, Inch	10% of Tooth Land	20% of Tooth Land	33% of Tooth Land
245	Kelly	T-38	J-85																													
91	"	F-84F	J-65WD	900		1011			1011																		MF					
96	"	B-52H	TF-33P3	1100																							MF					
97	"	C-123K	R-2800	800																												
99	"	T-38	J-85	500	472														F								M		F			
112	"	T-38	J-85																													
233	"	T-38	J-85	2400	2400														MF										MF			
234	"	C-5	TF-39																								MF					MF
235	"	C-5	TF-39																		F											
236	"	T-38	J-85	1600		1600																										
237	"	T-38	J-85	1600		1600	1600		1600																							
238	"	T-38	J-85	2400	2400														MF										MF			
193	Tinker	HH-53	T-64	400	400																											
194	"	RC-135C;B-52H	TF33-P9-P3	420															M										M			
195	"	RC-135C;B-52H	TF33-P9-P3	500			500												M		F								M			
196	"	F-4	J-79	600			600																					MF				
197	"	F-4	J-79	1500	1000																						MF					
198	"	F-4	J-79	600	450		600	450											MF										MF			
199	"	KC-135;B-52	J-57	1800	800		1800	800											M		F								MF			
200	"	KC-135	J-57	1800			1800																									
129	ARADMAC	UH-1 C, H	T-53																M										M			
132	"	UH-1 B, C, F	T-53																M										M			
133	"	UH-1 B, C, D	T-53																MF										MF			
134	"	UH-1	T-53																M										M			
135	"	UH-1B thru F	T-53	1100										MF															MF			
136	"	CH-47	T-55	1100												F						MF							MF			
137	"	CH-47	T-55	1100																		MF							MF			
142	"	UH-1A thru D	T-53			2500													MF										MF			
144	"	UH-1	T-53																MF										MF			
145	"	UH-1	T-53																MF										MF			
146	"	UH-1B thru F	T-53	1100										MF															MF			
147	"	UH-1C, E	T-53	1100										MF															MF			
214	United	DC-8	JT-4-3	3000	3000				2260								F													F		
160	AiResearch	727*	GTCP-85	3000	2200		3000	3000			MF								MF										MF			
161	"	Lear Jet	T-76	1600	50		1600	50																			MF		MF			
162	"	F-27, -28*	GTP-30	2500	100				100								MF										MF		MF			

TABLE B-6. SPLINE HISTORY, WEAR MEASUREMENT AND REJECTION CRITERI

210	Alameda	P-3	T-56	2000	4500		4500		3000																		F		F			
201	Amer. Air	707, 727	JT-3D, -8D	6400	6400	8500																										
108	Bendix	CF-5	J-85	400			400																									
110	Bendix	CF-5	J-85																													
227	N. Island	F-8	J-57														F												M			
215	United	727, 737	JT-8D		1000	8000		1000	8000		MF																		MF			
216	United	727, 737	JT-8D			2000			2000										MF										MF			

M=Male
F=Female

2

JECTION CRITERIA, AND CORRECTIVE RECOMMENDATIONS BY OTHER ORGANIZATIONS

			REJECTION CRITERIA									CORRECTIVE ACTION			CORRECTIVE TECHNIQUES														REMARKS	FORM
Vinco Gage	Visual	Not Specified	Few Thousandths, Inch	10% of Tooth Land	20% of Tooth Land	33% of Tooth Land	50% of Tooth Land	90% of Tooth Land	Knife Edge	Individuals Discretion	Not Specified	Current	Proposed	None	Alignment	Crowned Spline	Cut and Replace	Grease	Hardness	Material	Muff	Oil Mist	Plating Repair	Redesign	Research Program	Seal	Surface Treatment	Wet Pad		
												MF			MF			MF											Alleviate misalignment, enhance lubrication.	245
	MF									MF			MF																Will provide a measuring tool.	91
	MF						MF						MF											MF		MF	MF		"O" Ring; T. O. 8A6-10-2-502 Nov. 1963; Possible Nylon Coating.	96
														MF															Gold plate and Parkerizing have been tried.	97
	M		F				M					MF				M		MF											Nylon Coating, greases, see Appendix E.	99
												MF	MF		MF														Microseal 100-1; Nylon Coating; possible wet splines.	112
			MF										M											M		M			Shorter spline, thinner teeth, silver flash, grease seal, vent hole.	233
	MF					MF							MF																ECP 90 proposes: harder splines, oil circulation holes and oil nozzle.	234
													MF																ECP 90 proposes lubricant nozzle for radial gearshaft spline.	235
																														236
																														237
			MF										M											M		M			Shorter spline, thinner teeth, silver flash, grease seal, vent hole.	238
														MF															New helicopter; operate accessory to failure; no OH.	193
			M									MF	MF		MF													MF	Regrease every 300 hrs. Operate accessory to failure; no OH.	194
			M											MF															Operate accessory to failure; no OH.	195
		MF											MF															MF	Replacement controlled by male spline on Survey Form No. 198.	196
	MF										MF		MF											M					Lengthen male spline if misalignment is not excessive.	197
			MF										MF															MF	Over 3000 CSDS in service.	198
			MF										MF				F											MF	Tried Plastilube Moly No. 3; oil-mist; repair female by welding.	199
													MF								MF								Pesco proposes new design to P&W; P&W will propose to Tinker.	200
			M									MF					MF												SEO A-GEN-E0125.	129
			M									MF					MF													132
			MF									MF					MF												SEO A-GEN-E0125.	133
			M									M					MF												TM 55-6115-233-50.	134
			MF																											135
			MF																											136
			MF										MF														MF			137
			MF									M	MF														MF		Dry film on male.	142
			MF										MF														MF		Better wear surfaces.	144
			MF																											145
			MF																											146
			MF																											147
				F								MF									MF					MF			Using muff and grease retention "O" ring.	214
			MF									MF												MF					Replacing long shaft with shorter one to minimize orbiting.	160
	MF		MF									MF													MF				SwRI Research (see Appendices A and E).	161
	MF		MF										MF							MF									Go-No-Go Gage for new splines only.	162

CTION CRITERIA, AND CORRECTIVE ACTIONS TAKEN BY NAVY AND OTHER ORGANIZATIONS

Vinco Gage	Visual	Not Specified	Few Thousandths, Inch	10% of Tooth Land	20% of Tooth Land	33% of Tooth Land	50% of Tooth Land	90% of Tooth Land	Knife Edge	Individuals Discretion	Not Specified	Current	Proposed	None	Alignment	Crowned Spline	Cut and Replace	Grease	Hardness	Material	Muff	Oil Mist	Plating Repair	Redesign	Research Program	Seal	Surface Treatment	Wet Pad	Remarks	Form
	F		F									M																		210
												MF									MF					MF			Best combination: Muff + 343X grease + boot seal.	201
														MF																108
														MF																110
			M									MF																		227
			MF									MF											MF						Machine off, spline taper and hard nickel and chrome flash.	215
			MF									MF											MF						Chrome flash male and female.	216

APPENDIX C

SUMMARY OF LUBRICANT MANUFACTURERS SURVEY RESULTS

		Page
1.	General Recommendations	C-2
2.	Current Greases Recommended for Spline Operation	C-6
3.	Suggested Components for Spline Greases	C-8

Brand names are cited as reported. They do not imply endorsement or otherwise by the authors.

TABLE C-1. GENERAL RECOMMENDATIONS

Questions	Chevron
1. Spline design recommendations that would enhance lubricant effectiveness:	It was recommended that oil flow channels be provided across the face of the spline teeth in order to allow new lubricant to cross the teeth rather than to let the original lubricant stay stagnant between the spline teeth. Trap areas should be avoided. The amplitude of sliding should be increased with a decrease in load. Higher frequencies of oscillation could be important.
2. Lubrication techniques or practices that would improve spline performance:	It is recommended where possible, that the spline be submerged in an oil of low viscosity.
3. Importance of spline materials.	Reference is made to Heinemann 1967. This German document contains considerable information relating to fretting phenomena and the types of apparatus used for setting same.
4. Importance of material hardness:	In general, high hardness reduces fretting (reference is also made to Heinemann).
5. Importance of surface finish:	There is no significant effect within a normal range of 0 to 15 microinch CLA.
6. Effectiveness of spline coatings (platings, reaction films, polymers, bonded solid lubricants) and/or compatibility of the coatings with spline lubricants:	It is believed that an elastic film can be effective. A film described here would have to be an elastomer type that would be bonded directly to both the male and female connection. This concept being similar to a motor mount whereby the elastic material is bonded between the two members thereby absorbing the relative motion between the two parts.

TABLE C-1. GENERAL RECOMMENDATIONS (Cont'd)

Shell	Texaco
Some means of pumping the lubricant over the spline surface - possibly a spiral groove machined in the outer surface.	Reduce spline misalignment.
Operate the spline in an oil bath wherever possible.	Provision of adequate grease cavity and directed grease flow so as to purge old grease at relubrication. Use of grease having good feedability, shear susceptibility, or perhaps high bleeding rate.
We are not qualified to answer this question. We recommend that this be directed to spline designers.	Material selection should be guided by fretting corrosion test results. Steel on steel is generally used, and no recommendations of specific steels were made.
Refer to Question 3.	Information on the effects of hardness in minimizing fretting wear is meager; however, it appears that increased hardness is associated with lower susceptibility to attack.
Refer to Question 3.	No recommendations can be made on this point since both smooth finishes and rough finishes are claimed to minimize fretting.
Surface modifications have been shown to be effective during break-in, however, they may have an adverse effect on lubricant performance. Each case must be evaluated for suitability.	Coatings may serve to delay the inception of fretting until the coating is worn away.

TABLE C-1. GENERAL RECOMMENDATIONS (Cont'd)

Questions	Chevron
7. Importance of clearance:	We believe that an increase of volume (in effect, more backlash between mating splines) would not provide additional protection for the spline connection.
8. Effects of contaminants (dust, sea water, chemicals, others):	No comment.
9. Test methods used to evaluate spline lubricants:	Chevron's fretting apparatus is recommended, reference Chevron Research Company Drawing No. RE 690862 dated 2-4-69. This device utilized a 1/4-in steel ball locked in a collet which in turn is allowed to vibrate in an elliptical motion having a major axis of 0.015 in. The ball rides against a stationary Timken block. One drop of oil is placed between the ball and the block after which a drive motor is started containing an eccentric producing the elliptical motion between the ball and the block specimen. A vibration sensor is utilized to determine the increase in the vibration after excessive fretting is encountered.
10. What spline data and operating conditions do you require in order to formulate a grease for a particular application:	Temperature, frequency, load, atmosphere, and duration.
11. Advantages or disadvantages of oil lubrication of splines:	Less fretting corrosion can be expected in fresh oil. This implies that as new oil is directed to the intimate site between the mating parts, less fretting and corrosion can be expected.

TABLE C-1. GENERAL RECOMMENDATIONS (Cont'd)

Shell	Texaco
Refer to Question 3.	Tighter fits (reducing "jiggling") are preferable.
Contaminants are harmful. Dust, sea water chemicals, and other contaminants should be excluded from the lubricant and spline. Careful handling and storage of the lubricant and adequate spline seals are important.	The presence of contaminants such as dust, sea water, chemicals, etc., is generally detrimental to spline life, but no specific recommendations or experience were given.
Oscillating bearing tests, Mean Hertz Load-Wear Index.	Rigs and methods used for studying fretting were recommended - in particular, the Sikorsky Universal Fretting Corrosion Antifriction Bearing Tester (SKP-1721-1).
Formulation parameters are dictated by factors of performance other than spline data. For example, rubber swell, temperature range evaporation loss, etc.	No specific data recommended. Their approach would be to select an existing lubricant that performed satisfactory under similar conditions. The small volume of spline lubricants precludes a more elaborate approach to development of spline lubricants.
The ability of oil to lubricate splines is superior to grease provided that seals capable of retaining the oil in the spline are employed.	No comment.

TABLE C-2. CURRENT GREASES RECOMMENDED FOR SPLINE OPERATION

Item No.	Lubricant Description	Texaco	Texaco
1	Manufacturer's Identification	Novatex 1	Regal Starfak 2 (TG-7478)
2	Type (Grease, oil, solid film, etc.)	Grease	Grease
3	Military or other specifications		
4	Base Stock	Paraffin oils	Mineral oil 80%
5	Thickeners	Calcium soap of a hydroxy-type acid, 10.7%	Sodium soap 13.8%, calcium soap 2.8%
6	Additives	Oxidation inhibitor	Rust inhibitor
7	Other components		
	Lubricant Properties		
8	API Gravity		
9	Flash Point		
10	Fire Point		
11	Pour Point °F	-5	
12	Viscosity, cs at 100°F	330 SSU	303
13	Viscosity, cs at 210°F	53.7 SSU	
14	Viscosity index		
15	Acid No.		
16	Base No.		
17	Interfacial Tension		
18	Copper Corrosion (212°F)		
19	Steel Corrosion		
20	Color	Greenish-brown	
21	Dropping point, (min)°F	286	358°
22	Worked Penetration	337	281
23	Bomb Oxidation, Pressure Drop in 100 hrs., in psi (max)	2	3
24	Water Resistance at 100°F grease loss percent by wt (max)	1.8	5
25	Evaporation, % at 250°F (max)		
26	Oil separation, % at 210°F (max)		
27	Low temperature torque (indicate temperature °F)		
28	Starting Torque, g-cm		4425 at -20°F
29	Running Torque, g-cm		738 at -20°F
30	Load Wear Index (min)		
31	Worked Stability (max)		
32	High Temperature Performance at 250°F (hrs)		
33	Apparent Viscosity at -65°F poises at 20 reciprocal seconds		
34	Apparent Viscosity at -65°F poises at 50 reciprocal seconds		
35	Steel on steel Wear		0.39 mm
36	Rust Preventive Properties		Pass 1
	Spline Wear Performance		
37	Test Apparatus		
38	Wear Performance in Air, describe		
39	Wear Performance in Fuel, describe		
40	Fretting corrosion test (Sikorsky)	Approx. 500 hr	690
41	Remarks		Range of Application temperatures -30 to 300°F

TABLE C-2. CURRENT GREASES RECOMMENDED FOR SPLINE OPERATION (Cont'd)

Item No.	Texaco	Shell	Shell	Shell
1	Uni-Temp 500	Aeroshell 14	Aeroshell 17	Aeroshell 22
2	Grease	Grease	Grease	Grease
3	United Kingdom DTD 900 MIL-L-3545		MIL-G-21164	MIL-G-81322
4	High molecular weight, organic compound plus synthetic non-silicone oil	Mineral	Synthetic ester	Synthetic hydrocarbon
5	Sodium soap	Calcium soap	Microgel	Microgel
6				
7			Molybdenum Disulfide	
8				
9				
10				
11				
12				
13		3.1	3.1	7.7
14				
15				
16				
17	24 hrs at 212°F			
18	Pass	Pass	Pass	Pass
19		Pass	Pass	Pass
20	Blue-black			
21	381°	500+	500+	500+
22	335	289	295	277
23	27 (50 hrs)	2	8.5	2 (200 hrs)
24	2.5	7.2	1.0	1.2
25	3.4 at 300°F, 100 hrs	5.1 at 210°F, 22 hrs	0.8 at 210°F, 22 hrs	4.2 at 350°F, 22 hrs
26	15 at 300°F, 30 hrs	3.5, 30 hrs	2.3, 30 hrs	5.9 at 350°F, 30 hrs
27				
28	700 at -40°F		4960 at -100°F	2443 at -65°F
29	200 at -40°F		740 at -100°F	507 at -65°F
30	40 Kg		50 Typical 85	39
31	400+	301	316	362
32	at 350°F, avg hrs to failure 1050	1700 hrs + (200°F)	1000 hrs +	800 hrs + (350°F)
33	at -40°F, 9000			
34				
35	40 Kg, 30 min, 0.84 mm			0.67
36		Pass	Pass	Pass
37				
38				
39				
40				
41	-65° to 350°F			

TABLE C-3. SUGGESTED COMPONENTS FOR SPLINE GREASES

Shell:

Operating Conditions:	In Air		In Fuel	
Speed, rpm	2000	4000	2000	4000
Contact, Stress, psi	1000	5000	1000	5000
Temperature, °F	200	300	200	200

Lubricant Component				
Base Stock	X	X	X	X
Thickening Agent	X	X	X	X
Oxidation-Inhibitor	X	X	X	X
Corrosion Inhibitor	X	X	X	X
Detergent				
Dispersant				
Rust Inhibitor	X	X	X	X
Oiliness Agent				
Extreme Pressure (EP)..	X	X	X	X
Tackiness Agent				
Antiwear	X	X	X	X
Solid Lubricants (fillers).				
Metal Deactivators	X	X	X	X
Alkaline Agent				

Chevron: None Suggested

Texaco: None Suggested

APPENDIX D

SUMMARY OF SQUADRON MAINTENANCE PRACTICES AT NORFOLK NAVAL AIR STATION

		Page
1.	Aircraft: E-2A, E-2B; Engine: T-56-A-8A	D-2
2.	Aircraft: H-46 and H-3; Engine: T-58	D-3
3.	Aircraft: F-4-B/-J; Engine: J79-8	D-4

Brand names are cited as reported. They do not imply endorsement or otherwise by the authors.

TABLE D-1. AIRCRAFT: E-2A, E-2B; ENGINE: T-56-A-8A

QUESTION ↓ ACCESSORY →	Constant Speed Drive	Generator	Starter	Hydraulic Pump	Fuel Pump
Do you remove and replace the accessory (Yes or No)?	NA	YES	YES	YES	YES
Do you replace any splines between the accessory and mating component (Yes or No)?	NA	NO	YES	NO	NO
Before the accessory is replaced, how is female spline on the major component cleaned? (Explain).	NA	PD-680 and ACID BRUSH	PD-680 and ACID BRUSH	PD-680 and ACID BRUSH	PD-680 and ACID BRUSH
What document specifies spline cleaning instructions (NAVAIR, T.O., etc.)?	NA	NA-02B-5DB-2	NA-02B-5DB-2	NA-02B-5DB-2	NA-02B-5DB-2
What cleaning compounds or solvents are used in cleaning splines (MIL spec., FSN)?	NA	TYPE II P-D-680 6850-274-5421	TYPE II P-D-680 6850-274-5421	TYPE II P-D-680 6850-274-5421	TYPE II P-D-680 6850-274-5421
How often is the splined connection between the accessory and mating component lubricated (Hrs)?	NA	WHENEVER THE COMPONENT IS REMOVED	WHENEVER THE COMPONENT IS REMOVED	WHENEVER THE COMPONENT IS REMOVED	REMOVED
What document gives lubrication instructions (NAVAIR, T.O., etc.)?	NA	NA-02B-5DB-2 T56-PPB-80, REV A	NA-02B-5DB-2 T56-PPB-80, REV A	NA-02B-5DB-2 T56-PPB-80, REV A	
What spline lubricant do you use (MIL spec, FSN, and/or Mfg. P/N)?	NA	MIL-G-81322	MIL-G-81322	MIL-G-81322	
How is lubricant applied? (Explain).	NA	WITH ACID BRUSH	WITH ACID BRUSH	WITH ACID BRUSH	

TABLE D-2. AIRCRAFT: H-46 AND H-3, ENGINE: T-58

QUESTION ↓ ACCESSORY →	Constant Speed Drive	TACH. Generator	Starter	Hydraulic Pump	Fuel Pump
Do you remove and replace the accessory (Yes or No)?	NA	YES	NA	NO	YES
Do you replace any splines between the accessory and mating component (Yes or No)?	NA	NO	NA	NO	NO
Before the accessory is replaced, how is female spline on the major component cleaned? (Explain).	NA	NO	NA	NO	USING CLEANING SOLVENT AND ACID BRUSH
What document specifies spline cleaning instructions (NAVAIR, T.O., etc.)?	NA	NONE	NA	NONE	02B-105-AHB-2 NA
What cleaning compounds or solvents are used in cleaning splines (MIL spec., FSN)?	NA	NO	NA		PD-680
How often is the splined connection between the accessory and mating component lubricated (Hrs)?	NA	NO	NA	NO	EVERY CAL INSP 51 WKS OR 500 HRS
What document gives lubrication instructions (NAVAIR, T.O., etc.)?	NA	02B-105-AHB-2	NA	NONE	02B-105-AHB-2 NA
What spline lubricant do you use (MIL spec, FSN, and/or Mfg. P/N)?	NA	PLASTILUBE MOLY 3	NA	NONE	MIL L-23699 PLASTILUBE MOLY 3
How is lubricant applied? (Explain).	NA	ACID BRUSH	NA	NONE	ACID BRUSH

TABLE D-3. AIRCRAFT: F-4-B/-J; ENGINE: J79-8

QUESTION ↓ ACCESSORY →	Constant Speed Drive	Generator	Starter	Hydraulic Pump	Fuel Pump
Do you remove and replace the accessory (Yes or No)?	YES	YES	NA	YES	YES
Do you replace any splines between the accessory and mating component (Yes or No)?	NO	NO	NA	NO	NO
Before the accessory is replaced, how is female spline on the major component cleaned? (Explain).	CLEANING SOLVENT AND STIFF BRISTLE BRUSH	CLEANING SOLVENT AND STIFF BRISTLE BRUSH	NA	CLEANING SOLVENT AND STIFF BRISTLE BRUSH	CLEANING SOLVENT AND STIFF BRISTLE BRUSH
What document specifies spline cleaning instructions (NAVAIR, T.O., etc.)?	NAVAIR 02B-105-AGC-6		NA		
What cleaning compounds or solvents are used in cleaning splines (MIL spec., FSN)?	SOLVENT (P-D-680) OR EQUIVALENT FSN 7920-570-2395	SOLVENT (P-D-680) OR EQUIVALENT FSN 7920-570-2395	NA	SOLVENT (P-D-680) OR EQUIVALENT FSN 7920-570-2395	SOLVENT (P-D-680) OR EQUIVALENT FSN 7920-570-2395
How often is the splined connection between the accessory and mating component lubricated (Hrs)?	PRIOR TO INSTALLATION	PRIOR TO INSTALLATION	NA	PRIOR TO INSTALLATION	PRIOR TO INSTALLATION
What document gives lubrication instructions (NAVAIR, T.O., etc.)?	NAVAIR 02B-105 AGC-6	NAVAIR 01-245FDA-6-4.1	NA	NAVAIR 01-245FDA-6-4.1	NAVAIR 01-245 FDA-6-4.1
What spline lubricant do you use (MIL spec, FSN, and/or Mfg. P/N)?	PLASTILUBE MOLY 3 FSN 9150-889-3516 or 9150-828-8045	CSD TO ALTERNATOR SUNSTRAND ANTI FRETTING COMPOUND 688272	NA	PLASTILUBE MOLY 3	PLASTILUBE MOLY 3
How is lubricant applied? (Explain).	SMALL BRUSH	SMALL BRUSH	NA	SMALL BRUSH	SMALL BRUSH

APPENDIX E

SUMMARY OF CURRENT IMPROVEMENT PROGRAMS

		Page
1.	Engine: JT-3D	E-2
2.	Engine: JT-8D	E-2
3.	Engine: JT-9D	E-2
4.	Engine: J-48	E-2
5.	Engine: J-57	E-3
6.	Engine: J-65	E-4
7.	Engine: J-71	E-6
8.	Engine: J-79	E-7
9.	Engine: J-85	E-10
10.	Engine: R-1820	E-11
11.	Engine: TF-39	E-12
12.	Engine: T-53	E-12
13.	Engine: T-56	E-13
14.	Engine: T-58	E-15
15.	Engine: T-76	E-15
16.	30 kva CSD, Self-Aligning	E-16
17.	SST Shaft Power	E-16

Brand names are cited as reported. They do not imply endorsement or otherwise by the authors.

1. Engine: JT-3D
Description. American Airlines, Boeing 707-123/720/323, BM-2994110, 12-15-59.
Title, Engine, and Components. Maintenance Manual-Removal/ Installation engine driven hydraulic pump-boot and seal installation. Engine JT-3D and JT-8D.
Survey Form No. 201 "Trouble Free Installation"
Summary. American Airlines engineers developed a boot-grease seal which is slipped over the male interface spline on the hydraulic pump. After the mating splines are greased, the pump is installed into place. The boot mates with the cylindrical portion of the female spline on the gearbox. On a large number of interface spline connections there is a void in the general vicinity of the spline connection where the lubricant can migrate as a result of centrifugal force. The boot concept was recommended by American Airlines and is now incorporated in the Boeing Maintenance Manual.

A newer version of the dogbone-boot connection will incorporate a "muff spline" at the interface connection with a snap ring.

The original operating life was 500 hours, now extended to 6400 hours. (A copy of this manual was not obtained.)

2. Engine: JT-8D
Description. Sundstrand SBN 24-917, 1971.
Title, Engine, and Components. CSD Model No. 40 AGD10 used on the B-737 aircraft.
Summary. The service bulletin contains instructions for the rework of the input spline shaft which provides the same engagement length with the engine splines as do other model CSD's. (A copy of this bulletin was not obtained.)

3. Engine: JT-9D
Description. Sundstrand SBN 24-1015, 1971.
Title, Engine, and Components. CSD Model No. 60 AGD09 used on the 747 aircraft,
Summary. Instructions are given to replace the existing spline shaft retaining rings with new improved strength retaining rings. (A copy of this bulletin was not obtained.)

4. Engine: J-48
Description. Navy LED NA 03-5CA-52/PN 4 PEN., 7-24-69.
Title, Engine, and Components. Rework of starter on J-48 engine.
Survey Form No. 122

Summary. To provide wear tolerance for armature spline on Jack & Heintz D26, 27, and D31 starters during overhaul. Check armature spline (Items 36 and 37, Fig. 2-7) for wear by using two 0.085 in. diameter by 0.312 in. long pins and placing pins 180° apart in top land of armature spline. Measure distance between outer edges of pins across armature shaft. Replace armatures that measure less than 0.710 in.

On armature P/N 20031-1023 replace removal spline P/N 20031-1027 with new spline of same number if old spline is worn beyond permissible wear dimension.

5a. Engine: J-57
Description. Air Force EPN H-78-1, 4-29-70.
Title, Engine, and Components. Pratt and Whitney program to evaluate Microseal 100-1; fuel pump on J-57 engine.
Survey Form No. 199
Summary. P & W program to evaluate the effectiveness of Microseal 100-1 in reducing Pesco fuel pump spline wear. Program used two fuel pumps—one with Microseal 100-1 and one without. Test performed up to 500 hours. No results were available.

5b. Engine: J-57
Description. Navy PPC No. 95.
Title, Engine, and Components. *Hub at location "C" in J-57 engine.*
Survey Form No. 189
Summary. Reported to have excessive spline wear on hub P/N 500407 located in section "C". Axial motion is experienced within this connection. This PPC reportedly specified cutting off a portion of the hub and replacing it with another spline connection containing a sleeve. The sleeve is pinned in eight places. (A copy of the PPC was not obtained.)

5c. Engine: J-57
Description. Navy PPC No. 75 and 80.
Title, Engine, and Components. Fuel pump on J-57 engine.
Survey Form No. 227
Summary. It reportedly eliminated the grease and provided a wet pad. In service for 300 hours plus. Spline problems eliminated. Pressure lubricated about 10 psi. (A copy of the PPC was not obtained.)

6a. Engine: J-65
Description. Navy, Wright J-65 EBN 279, 9-25-59.
Title, Engine, and Components. J-65-W-4B/W-16A accessory gearbox fuel control drive gear. Fuel control.
Summary. Cut relief at fuel control spline, which will alleviate excessive wear.

6b. Engine: J-65
Description. Navy, Wright J-65 EBN 363, Buweps FWAE-4, 11-30-62.
Title, Engine, and Components. Accessory gearbox—Improvement of concentricity and squareness and oil mist spline lubrication. J-65-W-16A fuel pump, front and rear hydraulic pump.
Summary. Check run-out of fuel and hydraulic pump pads on accessory gearbox. Jig set up to drill holes for oil mist lubrication.

6c. Engine: J-65
Description. Navy J-65 EBN 319, Revision A, Amendment No. 1, BuWeps FAE-34, 6-25-65.
Title, Engine, and Components. Accessory gearbox splines and corresponding mating accessory spline; inspection and lubrication of Pesco and Thompson fuel pumps.
Summary. Lubricate female and male splines using Plastilube No. 3. Replace units when wear limits exceed 0.008. Different gages required to check splines on this J-65 engine.

6d. Engine: J-65
Description. Navy, Wright J-65 EBN 376, Revision B, AIR 4113, 10-10-69.
Title, Engine, and Components. J-65-W-16A fuel control drive shaft with universal joints. Fuel control.
Summary. Replacement of rigid drive shaft with universal joint drive shaft for fuel control.

6e. Engine: J-65
Description. Navy ACN 292, AIR 53681A/4113, 10-30-70 (Lycoming) ECP No. 33, Nov. 1970, Item No. 4).
Title, Engine, and Components. Lycoming CSD Model LD6-3, LD6-10, and LD6-10A.
Survey Form Nos. 207 and 170
Summary. Incorporate a spring-loaded muff with mating spline on the Lycoming output shaft of CSD.

6f. Engine: J-65
Description. Navy spline wear improvement data.
Title, Engine, and Components. J-65 accessory gearbox spline wear. Fuel pump, front, and rear hydraulic pump and generator drive.
Summary. Refer to Items 6g, 6h, and 8c. Excessive wear of generator spline was noted on J-65-W5 accessory box. As a result a CSD alternator was used and moved to the right-hand generator pad.

6g. Engine: J-65
Description. Navy EPN H-1, Aug. 70.
Title, Engine, and Components. J-65 accessory and accessory gearbox spline wear. Fuel pump, front and rear hydraulic pump.
Summary. Improvement of oil mist spline lubrication specified in NEB 363. Also, improve lubrication at magneto-generator and fuel control splines.

6h. Engine: J-65
Description. Navy EPN H-5, Sept. 70.
Title, Engine, and Components. J-65 accessory gearbox improved generator drive durability. Generator on J-65-W5.
Summary. Excessive spline wear and bearing failures have been experienced at generator drive locations on accessory gearboxes. Propose line bore bearing liners.

6i. Engine: J-65
Description. Navy J-65 PPC 62, Application: J-65-W-416 with fuel pump 022664-026-06; J-65-W-420 with fuel pump 022664-026-06, AIR 53632F/41131D, 9-28-70.
Title, Engine, and Components. Pesco fuel pump. Rework to accommodate 8-tooth spline and to pressure lubricate.
Summary. Rework to accommodate drive shaft with 8-tooth spline and to provide forced feed oil lubrication (wet pad) on J-65-PPC-67 accessory gearbox only.

6j. Engine: J-65
Description. Navy J-65-PPC-63, AIR 4113, 9-28-70.
Title, Engine, and Components. Fuel pump, Thompson.
Summary. Rework to accommodate drive shaft with 8-tooth spline and to provide forced feed oil lubrication on J-65-PPC-67 accessory gearbox only.

6k. Engine: J-65
Description. Navy J-65-PPC-64, AIR 4113, 9-28-70.
Title, Engine, and Components. Magneto-Generator, TMG LN-3 Ignition System.
Summary. Rework to accommodate drive gear with 8-tooth spline and to provide forced feed oil lubrication on J-65-PPC-67 accessory box only. Other models lubricated with Plastilube No. 3 after checking with No-Go involute spline gage. Eleven-tooth spline.

6l. Engine: J-65
Description. Navy J-65-PPC-67 and Amendment No. 1. AIR 53632F/41131D, 9-28-70.
Title, Engine, and Components. Accessory gearbox; rework to accommodate 8-tooth spline drive gears and pressure lubrication. Accessory gearbox Model J-65-W-16A and J-65-W-20.
Summary. Rework accessory gearbox to accommodate drive gears with 8-tooth splines. Provide force feed oil lubrication at fuel pump, front and rear hydraulic pumps and the magneto-generator locations. Amendment No. 1 changes AYC from 244 to 224 in Reference h.

7a. Engine: J-71
Description. Air Force T.O. 2J-J71-63E Supplement Technical Manual Overhaul, issued by OCAMA (OCNTTAA), 10-16-68.
Title, Engine, and Components. USAF J-71A-13, Allison engine.
Summary. This supplement was issued to allow the Specialized Repair Activity an increase in maximum wear limit of the internal spline of oil pump shaft P/N 6747679. Instructions: a. Pending availability of new or reworked oil pump shaft the allowable wear limit is increased from 10 to 25% of total thickness of spline as measured across top of spline. (Refer to Fig. 6-5-1 for definition of terms.) b. It is mandatory that serial numer of the engine into which shafts exhibiting wear between 10 and 25% are installed be recorded and furnished OCAMA (OCNTTAA).

7b. Engine: J-71
Description. Air Force, wire from Tinker AFB to Quonset Point, NAVAIREWORKFAC, July 69.
Title, Engine, and Components. Rework procedures for accessory drive shaft P/N 6743844 on J-71-63 engine.
Summary. Interim procedure to be used only until new shaft gear assemblies are available but not to exceed 50 shaft gear assemblies. Purpose of this supplement is to authorize the rigid welding of radial drive bench gear P/N 6728730 to the accessory drive shaft

gear P/N 6743844 when the mating splines of the shaft gear are worn in excess of the limits in T.O. 2J-J71-63, p. 6-6A/ 6-6B, Figure 6-5-1. Electron beam weld.

7c. Engine: J-71
Description. Navy T.O. 9H4-2-41-14.
Title, Engine, and Components. Muff design, J-71-A-13 engine.
Survey Form No. 181
Summary. It was reported that the T.O. specifies a "Muff" design. It was reported that no funds were available to make the design change. Oil pump to hydraulic pump. (A copy of the T.O. was not obtained.)

8a. Engine: J-79
Description. Air Force IROS Low Reliability item data, WUC No. 2373R, 1-13-70.
Title, Engine, and Components. CSD input shaft on Sundstrand CSD for F-4 aircraft, J-79 engine.
Survey Form No. 198
Summary. High condemnation rate due to worn splines. Three EUR's per month. Monthly cost $12,993. Reason for establishing IROS project is to investigate and reduce high condemnation rate of 85% at the time of overhaul. Because of worn splines, total issue date for both Field and Depot is now 2,199 shafts for one year.

8b. Engine: J-79
Description. Air Force and Navy, NATC ST-128R-70, 7-17-70.
Title, Engine, and Components. Engineering evaluation of wet input splines for Sundstrand 30 KVA CSD in the F-4J airplane with J-79-GE-10 engines. Sundstrand CSD wet spline.
Survey Form Nos.196 and 198
Summary. Flight tests were conducted to evaluate a prototype unit of an oil bath, wet spline configured, Sundstrand 30 KVA CSD to determine potential of the oil bath concept in reducing fretting corrosion on CSD input shaft splines, shaft axial vibration, and associated wear on locking pin and plug of Accessory Change No. 173. A total of 553 flight hours simulating fleet operating conditions were flown at NAVAIRTESTCEN using an F-4J airplane. An additional 2200 flight hours were accumulated on modified CSD units in fleet F-4J airplanes during an actual service suitability evaluation of the oil bath wet spline modification. Within the scope of this test, the oil bath wet spline modification significantly reduced the fretting corrosion of the CSD input shaft splines and is satisfactory. It did not however reduce the input shaft axial vibration

and associated wear on ACN 173 components. A lubricating oil loss problem was eliminated by local redesign of the CSD mounting flange. It is recommended that the oil bath wet spline modification be incorporated on all Sundstrand 30 KVA CSD units operating on J-79-GE-10 engines in F-4 airplanes. Additional testing should be conducted to define and eliminate the CSD input shaft axial vibration problem.

8c. Engine: J-79
Description. Navy J-79-PPB, No. 212 FAE-34, 12-6-65.
Title, Engine, and Components. Main fuel pump inspection and lubrication of drive splines. Fuel pump P/N 512D892.
Summary. Specify Plastilube Moly No. 3 and use standard micrometer to measure spline tooth wear across 4 teeth.

8d. Engine: J-79
Description. Navy NATC ST-5R-68, 1-23-68.
Title, Engine, and Components. Engineering evaluation of wet input splines for Sundstrand 30 KVA constant speed drives in the F-4J airplane with J-79-GE-10 engines; Sundstand CSD wet spline.
Summary. Limited experience with the Sundstrand 30 KVA CSD installed on J-79-GE-10 engines indicated fretting corrosion of input spline could limit service life. Test is to evaluate a modification to CSD which provides continuous oil to the input spline. Report contains results of first 150 flight hours of testing.

Two modified Sundstrand 30 KVA CSD's S/N B1015 and B679 were installed in F-4J BuNo. 153077 equipped with J-79-GE-10 engines. Airplane was not equipped with AWG-10 missile control system. Tests were conducted with prototype equipment which enabled cavity at the interface of the transfer gearbox and CSD to be filled with oil. Both test CSD's were equipped with the 0.125 in. diameter shear pin (Accessory Change 173) to prevent withdrawal of the CSD input shaft.

8e. Engine: J-79
Description. Navy J-79-PPB, No. 254, AIR 4113, 2-5-68.
Title, Engine, and Components. J-79 transfer gearbox CSD spline wear inspection. CSD for all J-79-GE-8 and 10 engines on F-4 aircraft.
Summary. Establish transfer gearbox (CSD) shaft spline wear limits to be used at organizational and intermediate maintenance levels providing availability of replacement transfer gearboxes having CSD spline wear within limits of References (a) or (b) Sundstrand and GE spline engagement.

8f. Engine: J-79
Description. Navy NATC ST-9R-69, 2-17-69.
Title, Engine, and Components. Engineering evaluation of wet input splines for Sundstrand 30 KVA CSD in F-4J airplane with J-79-GE-10 engines. Sundstrand CSD wet spline.
Summary. During test 118.5 hours were flown simulating fleet operating conditions to evaluate oil bath, wet spline configuration Sundstrand 30 KVA CSD unit. Unit was installed on a J-79-GE-10 engine in F-4J airplane to determine potential of oil bath concept in reducing fretting corrosion on CSD input splines. Wet spline equipped CSD has been flight tested for a total of 254.3 hours. Fretting corrosion has been significantly reduced as a result of the oil bath modification. Excessive oil loss from within the CSD/Transfer gearbox interface cavity was encountered throughout test phase. Testing should be continued to further evaluate oil bath modification's potential in reducing fretting corrosion and to resolve the excessive oil loss problem.

8g. Engine: J-79
Description. Navy ECP SMA 75071A-R3, 2-12-70.
Title, Engine, and Components. Incorporate wet pad on J-79 engine CSD connection for F-4B aircraft.
Summary. Minimize spline wear by incorporating a wet pad on the CSD input shaft. This proposal is for the CSD only.

8h. Engine: J-79
Description. Navy General Discussion Items, Part II, Item K10, Sheet 1 (311D626P4) Q.P. NAVAIREWORKFAC Ltr 500/FRC:jl, 10-15-70.
Title, Engine, and Components. Transfer gearbox horizontal shaft CSD spline wear limits.
Summary. Nature of Problem: Transfer gearbox horizontal shaft/CSD spline wear limits. (NARAIRSYSCHOMHQ msg 092230Z, Oct 68.) Present interim bulletin established revised spline wear limits for transfer gearbox/CSD horizontal drive shaft. Due to occasional problems in procuring new subject shafts, recommend revised limits be established as the new HOI and HMI limits and interim bulletin be rescinded.

Magnitude of Problem: The interim spline wear limits per IPPB261 were not intended to be permanently added to HOI and HMI manuals. Program: Accessory Bulletin No. 246, which directs incorporation of the oil wetted spline on all F4 Sundstrand CSD's should eliminate the rejection of CSD shafts and J-79 engine TGB drive shafts for spline wear.

Status: Interim PPB261 (Oct 68) was issued to provide expanded TGB CSD spline wear *limits as an interim* measure pending procurement of sufficient quantities of shafts to support overhaul schedules at which time the directive was to be cancelled. Contractor recommends that ASO insure that necessary action has been taken to procure shafts in sufficient quantities to support the overhaul schedule and that IPPB261 be cancelled.

8i. Engine: J-79

Description. Navy communication from Quonset Point, NAVAIREWORKFAC; Ref. 312/JAW:slm, 2-5-71.

Title, Engine, and Components. Wear fixes for J-79 engine splines.

Summary. All new designs are using wet or lubricated splines. Fixes: a. Muff splines—added "O" ring and grease panels-primarily fuel pumps, b. Scavenge pump—added grease, increased hardness; improve alignment, c. CSD-establish wear limits; add wet splines.

9a. Engine: J-85

Description. Air Force, 12-3-70.

Title, Engine, and Components. Kelly AFB Mechanical Branch test stand evaluation of Nylon and MIL-L-7808 oil for generator spline.

Survey Form No. 99

Summary. Depot experimentation is being performed to alleviate spline wear on the male spline on T-38 generators. Splines exhibited serious wear after 400 hours of test stand operation and in the aircraft. A Nylon-coated male spline was evaluated. The male spline was first reduced in size by electro-discharge machining. The resulting spline tooth surface finish was 125 rms. A Corvel NC primer was then applied to the male spline. Following this, a black Nylon coating (Corvel NCA-77-black-2178, Type 11, Nylon coating powder) was applied to the male spline resulting in a thickness of 0.010 in. The Nylon was applied by a fluid-bed process. Two 0.013-in. diameter laser-drilled holes (180° apart) were drilled through the male spline so that oil could seep into the spline connection from the gearbox.

A test stand (see T.O. 16G1-102-2) was used to test the Nylon-coated spline. The test stand simulates actual operation using a generator and a hydraulic pump. The generator was loaded (6 KW) and cycled through its operational range of

6400 to 9600 rpm. The misalignment of the mating connection was unknown. Only one test was performed.

After 1400 hours of test stand operation, the coating was still intact and had not worn enough to expose the metal. In addition, the generator vibration was less when the Nylon-coated spline was used.

After 1400 hours of test stand operation, the un-coated spline at the opposite end of the Nylon-coated spline was worn. This spline is usually packed with a Westinghouse grease, P/N 922B818-1. Furthermore, it is believed that the misalignment was also somewhat relieved by the coating.

9b. Engine: J-85
Description. Air Force, G. E. ECP 85L-88 (rec'd 4-9-71).
Title, Engine, and Components. Improved A/B fuel pump spline shaft for J-85-GE-5C/-5E/-5F/-5G/-5H/-5J/-13 engines.
Survey Form Nos. 233 and 238
Summary. Excessive wear on the pump end spline of the A/B fuel pump shaft caused excessive part scrappage at overhaul, unscheduled engine removals, and mission aborts. Wear was attributed to interference due to misalignment, tolerance stackups, and loss of grease. It was proposed to reduce spline length and tooth thickness in order to reduce misalignment-induced interference; to add silver flash to minimize fretting, corrosion, and wear; to add a seal to prevent grease loss due to centrifuging; and to add a small axial vent hole to relieve pressure changes due to variations in temperature and altitude which could destroy the seal. The vent also serves to relieve excess grease at assembly. Proposed change not put into effect because of cost and belief that it might cause excessive wear of the more expensive female splines.

10. Engine: R-1820
Description. Navy NATC WST-99R-70, 6-23-70.
Title, Engine, and Components. Improvement of Constant Ratio Transmission (CRT). Sundstrand CSD.
Summary. This work unit was established to determine possible improvements to CRT shafts used on S-2D/E and P-2 airplanes and to solicit from industry product improvement type contract proposals for needed improvements. Investigations indicated need for improvement of the Bendix CRT shaft P/N 19E29-3J used on the S-2D/E airplanes but no need for improvement on P-2 shafts. The Bendix Corp. was awarded a contract for

design and construction of 4 improved 19E29-3K CRT shafts for use on S-2D/E airplanes. These shafts were tested for a total of 1400 flight hours and were satisfactory. The tests also resulted in a redesign of the Sundstrand CSD shaft which connects to the CRT output spline. The Bendix P/N 19E29-3K CRT shaft and the Sundstrand P/N 709374 CSD shaft are recommended for service use in the S-2D/E airplanes. Incorporate a grease seal.

11a. Engine: TF-39
Description. Air Force G. E. Program BS-17, 10-31-70.
Title, Engine, and Components. Inlet Gearbox Horizontal Shaft Spline wear on TF-39 engine.
Survey Form No. 234
Summary. This program identifies several potential changes for reducing spline tooth wear including a less stiff duplex ball bearing with increased radial clearance and less preload, a flexible gaskoseal ring (in place of the brass ring) for retaining oil in the spline mesh and sealing off fan pressurization air and an oil nozzle which will more than double oil flow for mesh lubrication. Alignment of the nozzle and its effect on wear is also to be evaluated. Grease seal.

11b. Engine: TF-39
Description. Air Force G. E. Program BS-4, 10-31-70.
Title, Engine, and Description. TF-39 and CF-6 engines. Gearbox shaft spline and journal wear. C-5A aircraft.
Survey Form No. 235
Summary. Official 150 Hour Gearbox Dynamometer Test and 1000 hour service test, showed indication of spline wear and bearing inner race rotation in specific areas. Spline wear was evident at the Inlet Gearbox horizontal and radial shaft spline due to inadequate lubrication. Additional oil jets will be provided to positively lubricate the IGB horizontal and radial shaft splines to eliminate fretting. Also, the horizontal shaft spline will be hardened to minimize wear.

12a. Engine: T-53
Description. ARADMAC SEO-A-GEN-E0125.
Title, Engine, and Components. Generator and starter-generator drive shaft spline repair procedure, T-53 engine.
Survey Form Nos. 129 and 133
Summary. Purpose is to clarify the acceptable wear tolerance for the splines of the drive shaft and provide a method of repairing those worn beyond tolerance : A. Drive shaft assembly. Repair the drive shaft spline if the pin-to-pin diameter is less

than 0.9030 in. using 0.0864 pins; B. Spline repair. If spline fails to meet dimensions: 1. Grind driven shaft down, 2. Install sleeve spline P/N 23050-1117, 3. Pin the sleeve in one place.

12b. Engine: T-53
Description. ARADMAC TM55-6115-233-50, 11-20-68.
Title, Engine, and Components. Generator Model No. 30010-000, T-53 engine.
Survey Form No. 134
Summary. Purpose is to repair excessively worn spline on drive shaft spline. Decrease length of worn spline shaft by 0.625 in. and counterbore and precision-hone shaft. After removal of worn spline area, thoroughly chill gear spline P/N 30300-1162 in dry ice. Press part in place, check dimensions and grind if necessary. Apply MIL-G-3545 grease and operate generator at 8,000 rpm with load of 300 amps at 30 volts for 5 minutes.

13a. Engine: T-56
Description. Navy DIR 894, 9-12-67, NAVAIRSYCOMREPAC (Mr. DeLong), NAVAIREWORKFAC, Alemeda.
Title, Engine, and Components. Investigate and report on excessive generator spline P/N 1582801-2. AC generator Type 28B 95-15. T-56 engine.
Survey Form No. 210
Summary. Alameda NW 03-SAS-22 specifies Pioneer No. 31 or MIL-G-3545 while NW 01-75PAA-2-4 p. 3-183 specifies MIL-G-21164. Alameda uses MIL-G-21164. Excessive spline wear was due to a combination of service usage and lack of lubricant. Centrifugal forces from rotation of the drive shaft causes some loss of lubricant. Recommend manufacturer review problem. Recommend MIL-G-81322 be used. Allison proposed a wet pad: EDR 6603, Item No. 5636.1.2.05.

13b. Engine: T-56
Description. Navy P-3 LES NA03-5AS-22/AL41-2-0070, 3-25-69.
Title, Engine, and Components. A-C generator, drive shaft, Microsealing of A-C generator, T-56 engine.
Survey Form No. 210
Summary. New generator's spline shall be coated with Microseal 100-1. If top land dimension of teeth on used generator is less than .020 or less than .025, replace drive shaft assembly.

13c. Engine: T-56
Description. Navy EPN, 3-31-70.
Title, Engine, and Components. T-56 starter shaft drive spline lubrication (Allison proposal). Starter (internal splines).
Summary. Grease lubricated splines do not provide adequate lubrication to prevent wear. Provide adequate lubrication to the drive splines by directing pressure oil from the reduction gear lube system into the spline cavity.

13d. Engine: T-56
Description. Navy EPN, 3-31-70.
Title, Engine, and Components. T-56 accessory drive spline lubrication (Allison proposal). Alternator and hydraulic pump.
Summary. Grease lubricated splines do not provide adequate lubrication to prevent wear. Propose to provide adequate lubrication to the drive splines by directing an oil spray to the spline cavity. Incorporate an "O" ring seal.

13e. Engine: T-56
Description. Navy, Allison Ltr. 12-11-70 to NASC AIR-5362.
Title, Engine, and Components. A6441FN-243 propeller
M.O.T. Ref. THO-1931L-JWE
Survey Form No. 208
Summary. Excessive wear on propeller hub splines. At least 35 hubs were returned to Allison for rework. Allison suggests the island spline wear limit be reduced, measurement be made between balls and recommends that a DIR be conducted on -248 propeller.

13f. Engine: T-56
Description. Navy, spline wear improvement data, Branch 331, 2-26-71.
Title, Engine, and Components. Allison T-56 starter and accessory drive splines.
Summary. Provide adequate lubrication to these splines which is not adequate by the grease packing method. This is a severe problem in the T-56 engines. The hydraulic pump and alternator drive splines trouble has been corrected by this flood-type lubrication.

13g. Engine: T-56
Description. Navy ACN 192
Title, Engine, and Components. T-56 engine driven compressor used on a P-3 aircraft.

Summary. It was reported that the ACN converted the spline connection to a wet pad. The compressor drive is manufactured by AiResearch. The splined shaft is capable of backing out similar to a typical CSD unit by means of a large screw thread. O.H. is 2400 hours or on failure. AiResearch suggested the Navy use the wet pad design. The design has been in use for some two years on the P-3C aircraft. The gearbox conversion was probably done at Alemeda or Norfolk. (A copy of ACN 192 was not obtained.)

13h. Engine: T-56
Description. Navy, message from MARAEREFTRANSRON ONE FIVE TWO to NAVAIRSYSCOMHQ, No. RUAOBMAO 749, Unclassified priority, 1-13-71.
Title, Engine, and Components. Safety UR/incident report. KC-130F aircraft.
Summary. Number four engine driven hydraulic pump light illuminated at 22,000-ft. level. Pump was secured and engine feathered. Three engine landing was made without further incident. Pump, hydraulic, engine driven, S.N. A1-308/W.U.C.90166/M.C.90166/P.N. 66WBD-300-1. Pump seized. The drive coupling spline was damaged slightly and the drive bushing spline was almost worn smooth. Shaft did not shear.

14. Engine: T-58
Description. Navy PPC No. 85.
Title, Engine, and Components. T-58 engine.
Survey Form No. 229
Summary. It was reported that this change requires 100% replacement of the Pesco spline connection and replaces it with a "muff" spline. Should process about 2000 per year. (A copy of the PPC was not obtained.)

15. Engine: T-76
Description. Navy Subcontracts, Southwest Research Institute: Navy Contract N00019-69-C-0404, AiResearch P. O. 967077; Contract N00019-70-C-0362, AiResearch P. O. 130688 and 130875.
Title, Engine, and Components. Investigation of spline wear in JP-5 fuel environment.
Survey Form Nos.161 and 218
Summary. The objective of this program was to develop systematic experimental data on the wear life of spline connections as influenced by spline design parameters, spline materials, and surface treatments, with the splines operating in a JP-5 fuel environment. A comprehensive program consisting of twelve test groups was

originally developed by AiResearch to provide a systematic evaluation of the relevant variables. Subsequently, the program requirement was changed by AiResearch such that some test groups were altered and many other test groups were deleted. As a result, only four test groups, namely: II, IX, III, and XIII have been performed. The results have been summarized in Appendix A, along with the results of several prior Navy-sponsored research programs conducted at SwRI.

16. Engine —
Description. Navy NATC ST-27R-69, 4-9-69.
Title, Engine, and Components. Evaluation of Sundstrand 30 kva CSD Redesigned "Self-Aligning" Input Spline Shafts. Sundstrand CSD wet spline.
Summary. This project was established by NAVAIRSYSCOM to provide for laboratory and flight testing of the redesigned "self-aligning" input spline shafts for the Sundstrand 30 kva CSD. This is a quarterly report of project status as required by AIRTASK A05-536-809. The 10 redesigned shafts, ordered from the Sundstrand Corp. will be delivered approximately 30 June 69. Laboratory testing, by the ARING Research Corp. will commence upon delivery of the shafts. Flight testing and evaluation will commence upon completion of laboratory testing. It is recommended that project work be continued.

17. Engine —
Description. Sundstrand Report No. AER 496-2, 3-31-68.
Title, Engine, and Components. SST shaftpower spline drive.
Summary. This report was the final test and design report for the Boeing Phase 2 SST. A kidney-shaped gearbox was examined at Sundstrand. It contained four mounting pads on one side, three of which utilized the Sundstrand breech-lock design while the fourth used a "Marman" type clamp. This gearbox is driven by shaft power from the engine. The splines within the shaft power are designed to accept 3 degrees of misalignment and transmit 453 hp. The splines utilized in this connection are crowned and are force-lubricated (wet pads) with about 2 gpm through the splines. (A copy of this report was not seen and is regarded industrial confidential.)

APPENDIX F

PREVIOUSLY SUBMITTED SwRI RECOMMENDATIONS

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1.	Misalignment of Interface Spline Connections on Aircraft Engines and Accessories	F-2
2.	Improved Liaison Between Navy Organizations Having Cognizance of Interface Splines	F-7
3.	Pitting Damage on Three Upper Spline Connections on the Main Rotor Mast on UH-1 Helicopters	F-10

January 29, 1971

File: 09-2866

Naval Air Systems Command
Department of the Navy
Washington, D. C. 20360

Attention: Mr. A. J. Koury, AIR-4117B

Subject: Recommendation No. 1 — Misalignment of Interface Spline Connections on Aircraft Engines and Accessories Contract N00156-70-C-2156

Dear Mr. Koury:

As part of our survey and analysis of aircraft spline failures under subject contract, we have found over 61 spline problem areas on various military aircraft. One of the causes of excessive spline wear is misalignment between the mating splines. We believe the problem warrants review by the Naval Air Systems Command in the interests of reducing maintenance and replacement costs.

Problem Area

The majority of the spline wear problems encountered in the survey have been interface splines that connect the engine or accessory gearbox to accessories such as starters, generators, hydraulic pumps, fuel pumps, etc. Some of the interface spline connections may exhibit misalignment in excess of that specified in the AND and MS Standards, thereby accelerating spline wear. Spline misalignment on overhauled gearboxes and accessories is generally not measured at the overhaul facilities visited to date.

Recommendations

It is recommended that the following corrective actions be considered:

1. Measurements should be made of the actual lateral and angular misalignments of all components containing interface splines. Measurements should be made after the components, i.e., gearbox and accessory, have been completely assembled after rework.

2. Lateral and angular misalignments should be held within the specified tolerances of the appropriate AND and MS Standards listed below:

Accessory Mounting Flange AND	Accessory Mounting Flange Type	Engine Accessory Drive AND	Engine Accessory Drive Type
10260	X	20000	X
10261	XI	20001	XI
10262	XII	20002	XII
10263	XIII	20003	XIII
10266	XVI	20006	XVI
10267	XVII	20007	XVII
10270	XX	20010	XX

Flange-Accessory MS	Flange-Accessory Type	Drive Pad-Accessory MS	Drive Pad-Accessory Type
3330	2.653 BC Square	3325	2.653 BC Square
3331	5.000 BC Square	3326	5.000 BC Square
3332	5.000 BC Round	3327	5.000 BC Round
3333	8.000 BC Round	3328	8.000 BC Round
3334	10.000 BC Round	3329	10.000 BC Round

3. Any suitable gaging device may be used to measure lateral and angular misalignments. An example of such a device is shown in the attachment.

4. To facilitate proper control, measurements should first be performed only at the Naval Air Rework Facilities.

5. In view of the cost of performing this operation, measurements should initially be confined to those spline connections identified by each NARF as having experienced excessive wear.

6. Once it is verified that improved alignment reduces spline wear, measurements should then be extended during replacements at the Intermediate Level Maintenance.

Background Details

1. Kelly AFB—According to personnel in the Mechanical Branch of Service Engineering Division, misalignment of the interface splines on accessories is not measured after the accessories have been overhauled and reassembled. Propulsion Branch personnel of Service Engineering reported that misalignment of interface splines on engines and gearboxes is not measured after these units have been overhauled and reassembled. Both branches reported that measurements of individual parts are checked against the tolerances of appropriate drawings and it is assumed that the installed unit will give satisfactory alignment.

2. Tinker AFB—Service Engineering Division personnel reported that spline misalignment on assembled accessories is not generally measured. Misalignment is controlled through tolerances on parts. Personnel have experienced spline misalignment problems with newer constant-speed drives (CSD's). In order to solve this problem, quick attach-detach mounting plates are used between the mating CSD and generator. One aligning plate is set in epoxy and attached to the CSD. Alignment is made by means of a dial indicator after which the epoxy is allowed to set. The same procedure is used on the generator with another aligning plate and the generator is then attached to the CSD.

3. Quonset Point NARF—Aerospace Engineering Powerplant personnel reported that misalignment on assembled units such as engines, gearboxes, and accessories is not generally measured. One exception is the J-65 engine gearbox. Spline misalignment is checked on this gearbox because misalignment problems have been encountered with each interface spline on the gearbox, necessitating considerable rework.

4. Pensacola NARF—According to Powerplant and Accessory personnel, spline misalignment is not generally measured on assembled accessories, engines, or gearboxes. Parts are measured to check conformity with appropriate drawing tolerances. Shafts are checked for straightness, and bearing bores are checked for fit and concentricity. On the basis of these operations, alignment of the installed accessory is assumed to be within the original limits.

5. American Airlines—Personnel from Aircraft System Engineering reported that misalignment of interface spline connections is not normally measured. The airline had experienced a severe interface spline problem at a hydraulic-gearbox connection. The misalignment of the female spline at

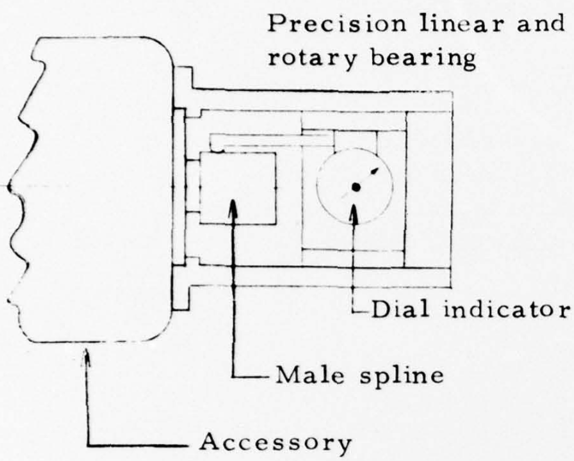
the gearbox was checked and found to be in excess of the AND Standards by a factor of 2 or 3 to 1. The problem was alleviated by improving the alignment.

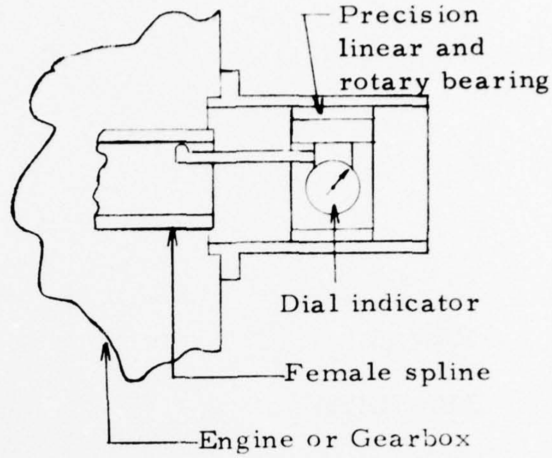
Very truly yours,

M. L. Valtierra
Senior Research Engineer
Department of Fluids and
Lubrication Technology

MLV:gt

Attachment





A ball-tipped stylus is employed to ride in contact with the sides of adjacent teeth. Misalignment is measured by axially traversing the stylus along the length of three or more equally spaced grooves. Differences in readings can be converted to give lateral and angular misalignments. Traversing in both the axial and circumferential direction is made possible by affixing the dial indicator to a precision linear and rotary bearing.

In the event that misalignment of a worn spline is to be measured, it would be necessary to slip a splined cylindrical sleeve over the spline for male splines and a splined plug into the female splines. Gaging measurements are made on the sleeve or plug. The splined sleeve or plug must fit closely with the spline being checked.

AN EXAMPLE OF SPLINE MISALIGNMENT GAGE

January 28, 1971

File: 09-2866

Naval Air Systems Command
Department of the Navy
Washington, D. C. 20360

Attention: Mr. A. J. Koury, AIR-4117B

Subject: Recommendation No. 2 — Improved Liaison Between Navy Organizations Having Cognizance of Interface Splines, Contract N00156-70-C-2156

Dear Mr. Koury:

As a part of our survey and analysis of aircraft spline failures under subject contract, we have found that the majority of the spline wear problems have been with interface splines that connect the engine or accessory gearbox to accessories such as starters, generators, hydraulic pumps, fuel pumps, etc. To the best of our knowledge, there is no one engineering organization in either the Navy or the Air Force that is responsible for the complete interface spline connection. Improved liaison between the existing groups could result in better control over factors affecting spline wear. We believe the problem warrants review by the Naval Air Systems Command in the interests of reducing maintenance and replacement cost.

Problem Area

Spline replacement rate is affected by many factors, including misalignment between mating splines, lubricant, lubricating method and frequency, material combinations, overhaul and inspection practices, and spline wear rejection criteria. Our survey to date indicates that control over these factors is exercised generally by several different groups, and no one engineering organization in the Navy or the Air Force is solely responsible for the complete interface spline connection.

Recommendations

It is recommended that the following corrective actions be considered:

1. Improve the liaison between groups responsible for interface splines to effect better control over all factors affecting spline wear and to prevent individual groups from taking actions which might result in increased overall spline maintenance costs.

2. In the event significant improved liaison cannot be obtained, it may be desirable to create an organization with the sole responsibility for interface spline connections.

Background Details

Spline wear problems can be kept to a minimum only by careful control over all of the factors which affect spline wear, including misalignment between mating splines, combination of spline materials, lubricant and lubrication practices, cleaning of splines when components are separated, and spline rejection criteria. Effective control over all of these factors is possible only if close liaison is maintained between all groups concerned with interface splines. However, the factors involved are diverse and control must extend from design through manufacture, initial acceptance inspection, operational maintenance, and depot rework. Control over the factors which affect spline wear is complicated by the fact that the major component (engine or gearbox) and accessories are usually manufactured by different companies. In addition, the two components are frequently overhauled and reworked by different organizations, often distant from one another, and lubrication and field maintenance are performed by other groups entirely.

It appears that a group could take individual action that could increase interface spline replacement rate. For example,

1. Either manufacturer might select a material, heat treatment, surface finish, or coating that would aggravate wear of the complete interface spline.

2. At depot or intermediate level maintenance facilities, local engineering specifications are often initiated in the interests of reducing local maintenance costs. These specifications may involve

reworking of splines or changes in tolerances, materials, heat treatment, surface finish, composition or thickness of coatings, and spline rejection criteria. Any one of the foregoing actions could result in increased overall spline replacement rate, and hence should not be taken without careful consideration of their overall effects.

Very truly yours,

MLV:dl

M. L. Valtierra
Senior Research Engineer
Department of Fluids and
Lubrication Technology

January 28, 1971

File: 09-2866

Naval Air Systems Command
Department of the Navy
Washington, D. C. 20360

Attention: Mr. A. J. Koury, AIR-4117B

Subject: Recommendation No. 3 — Pitting Damage on Three Upper Spline Connections on the Main Rotor Mast on UH-1 Helicopters, Contract N00156-70-C-2156

Dear Mr. Koury:

As part of our survey and analysis of aircraft spline failures under subject contract, we understand from ARADMAC, Corpus Christi, Texas, that the main rotor masts (Bell P/N 204-011-450) on UH-1B, C, D, E, F, and H helicopters require frequent replacement due to pitting damage encountered on the three upper spline connections. Similar problems are also experienced with main rotor masts (Bell P/Ns 204-010-410 and 209-010-450) used on other Model UH-1 and AH-1 helicopters. We believe the problem warrants review by the Naval Air Systems Command in the interest of reducing maintenance and replacement costs.

Problem Area

The main rotor mast (Bell P/N 204-011-450) on UH-1B, C, D, E, F, and H helicopters is reported by ARADMAC to require 50% replacement due to pitting damage experienced on the three upper spline connections (i.e., splines A, B, and C shown in the attachment). Each main rotor mast costs approximately $590, exclusive of labor cost. This main rotor mast is used on a vast majority of the helicopters overhauled at ARADMAC; in addition, similar pitting problems have been experienced on Bell P/Ns 204-010-410 and 209-010-450 which are used on other UH-1 and AH-1 series helicopters.

During overhauls performed at ARADMAC, MIL-C-11796, Class 2 corrosion-preventive compound is applied to splines A and B, and MIL-G-25537 grease is applied to spline C. Splines A and B are recoated with MIL-C-11796 corrosion-preventive compound at overhaul or disassembly of the main rotor mast assembly. Spline C is relubricated with MIL-G-25537 grease at 100-hr intervals.

Recommendations

It is recommended that the following corrective actions be considered:

1. Splines A, B, and C should all be lubricated with an appropriate grease during overhaul, and relubricated thereafter at 100-hr intervals.

2. Neither MIL-C-11796 corrosion-preventive compound nor MIL-G-25537 grease is a good spline lubricant; their use should be discontinued.

3. In place of the above, use MIL-G-21164 grease for service temperatures up to 250°F and MIL-G-81322 grease for service temperatures up to 350°F.

Background Details

Information gathered at ARADMAC may be summarized as follows:

1. The main rotor mast is fabricated of AISI 4340 (AMS 6415) steel, and the splines are not plated or coated by the manufacturer. During overhauls at ARADMAC, spline B is cadmium-plated in accordance with SEO No. UH-1-TO 211B.

2. Splines A, B, and C, located outside the transmission have shown pitting damage, with spline B exhibiting the greatest damage. Splines inspected at ARADMAC are rejected when the pit depth exceeds 0.010 inch as measured by a needle-pointed dial indicator. Pits of less depth are removed by blasting with dry glass beads.

3. During overhauls at ARADMAC, a MIL-C-11796 corrosion-preventive compound (only) is applied to splines A and B, while a MIL-G-25537 grease is applied to spline C in accordance with TM 55-1520-210-20, Chapter 8, Main and Tail Rotor Groups, and Chapter 2, Lubrication Instructions, respectively.

4. TM 55-1520-210-20 specifies that splines A and B be recoated with a MIL-C-11796 corrosion-preventive compound whenever the main mast assembly is overhauled. The main rotor mast assembly has an 1100-hr overhaul period, but can be overhauled more frequently whenever it has been run at excessive speed.

5. TM 55-1520-210-20 calls for in-service relubrication of spline C with a MIL-G-25537 grease at 100-hr intervals. These instructions specify hand-application of the grease, which is not a difficult operation.

6. Spline D, located in the transmission is oil-lubricated and has not been a serious maintenance problem.

Very truly yours,

M. L. Valtierra
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Department of Fluids and
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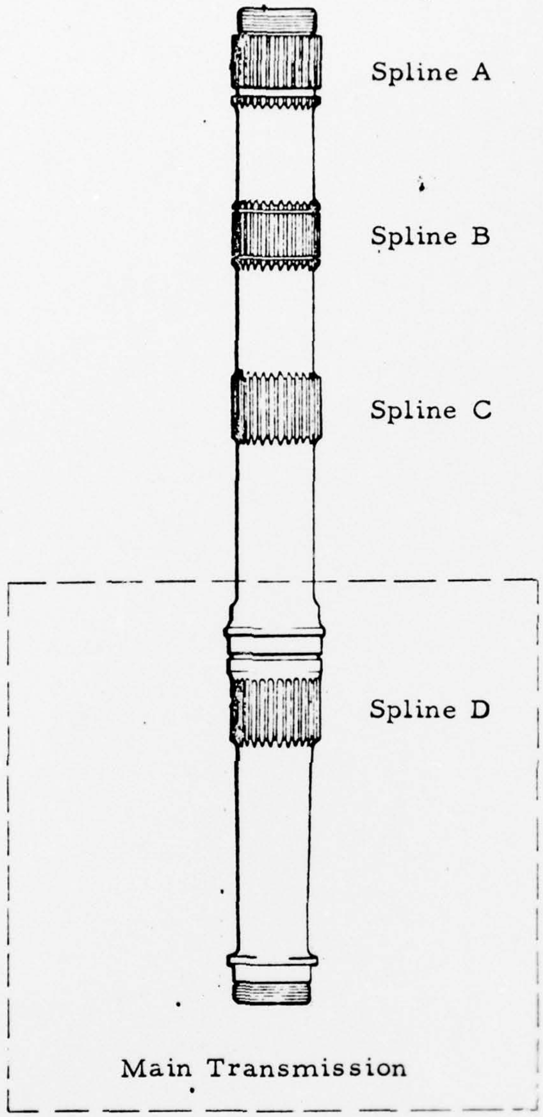
MLV:gt

Attachment



LOCATION OF SPLINES ON MAIN ROTOR MAST
OF UH-1 SERIES HELICOPTERS